

Supplementary material to: On the clinical interpretation of
overground gait stability indices in children with cerebral palsy

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2024-09-23

Contents

1	Introduction	2
2	Comparison with results from the literature	2
2.1	MoS	2
2.2	WBAM	3
3	Further details for the statistical analysis	4
3.1	Check age matching	4
3.2	Check size matching	5
3.3	Plot walking speed	6
3.4	Plot data for visual checks	7
3.5	Mean (SD) values for all indices and walking speed	16
3.6	Statistical modelling	17
3.7	Table of the model estimates	26
3.8	Alternative computations for the MoS	27
3.8.1	Using the HEE instead of the TOE marker	27
3.8.2	New table of the model estimates	28
3.8.3	MoS not based on timing (footstrike) but maximum	29
3.8.4	Table of the model estimates	33

1 Introduction

This document provides additional figures and information about the data. It also includes a comparison of our results on the margin of stability (MoS) and range of whole body angular momentum (WBAM) with available results in the literature.

2 Comparison with results from the literature

We focused on results available for typically developing individuals walking on a flat surface. We used WebPlotDigitiser (<https://apps.automeris.io/wpd4/>, Ankit Rohatgi) to extract the data available in the corresponding graphs.

2.1 MoS

We used the review of Watson et al [Wat23] to identify studies with similar computation choices (available in their Table 4) and condition (overground walking on flat surface).

- [Wat23] F. Watson, P.C. Fino, M. Thornton, C. Heracleous, R. Loureiro, J.J.H. Leong, Use of the margin of stability to quantify stability in pathologic gait - a qualitative systematic review, BMC Musculoskelet Disord. 22 (2021) 597. <https://doi.org/10.1186/s12891-021-04466-4>.

We compared our results with that of:

- [Bel14] E.J. Beltran, J.B. Dingwell, J.M. Wilken, Margins of stability in young adults with traumatic transtibial amputation walking in destabilizing environments, Journal of Biomechanics. 47 (2014) 1138–1143. <https://doi.org/10.1016/j.jbiomech.2013.12.011>.
- [Tis18] R. Tisserand, S. Armand, G. Allali, A. Schnider, S. Baillieux, Cognitive-motor dual-task interference modulates mediolateral dynamic stability during gait in post-stroke individuals, Human Movement Science. 58 (2018) 175–184. <https://doi.org/10.1016/j.humov.2018.01.012>.
- [Vug19] Y. van Vugt, J. Stinear, T. Claire Davies, Y. Zhang, Postural stability during gait for adults with hereditary spastic paraparesis, Journal of Biomechanics. 88 (2019) 12–17. <https://doi.org/10.1016/j.jbiomech.2019.03.001>.

All three studies were conducted in adults. The first two studies only provided data for the lat MoS while the third provided both ant and lat MoS. There was minor differences in the computation choices. [Tis18] used the midpoint between the TOE and HEE markers and [Vug19] used a point located 2cm lateral to the TOE marker. Instead [Bel14] and [San24] used the DMT5 (5th metatarsal head) marker for the lat MoS.

The results for the ant and lat MoS between our study ([San24]) and the previous studies were:

Study	ant.MoS	lat.MoS
[Bel14]		84
[Tis18]		86
[Vug19]	-3	50
[San24]	0.7	76

Our results for the ant and lat MoS in healthy controls appear similar to comparable studies.

2.2 WBAM

We compared our results with that of:

- [Her08] H. Herr, M. Popovic, Angular momentum in human walking, *Journal of Experimental Biology*. 211 (2008) 467–481. <https://doi.org/10.1242/jeb.008573>.
- [Rob09] T. Robert, B.C. Bennett, S.D. Russell, C.A. Zirker, M.F. Abel, Angular momentum synergies during walking, *Exp Brain Res*. 197 (2009) 185–197. <https://doi.org/10.1007/s00221-009-1904-4>.
- [Neg23] T. Negishi, N. Ogihara, Regulation of whole-body angular momentum during human walking, *Sci Rep* 13 (2023) 8000. <https://doi.org/10.1038/s41598-023-34910-5>.

We calculated the range of WBAM in the three planes from the above mentioned publications.

The three studies were conducted in healthy young adults on a standard flat surface. All three other studies used a non-dimensional normalisation factor of the WBAM based on Mass x Height (of CoM) x Walking speed. We used a non-dimensional normalisation factor based on scaling of body size (Mass x eL x sqrt(eLx acceleration of gravity)) to avoid factoring walking speed into WBAM. We have converted our results to the non-dimensional normalisation factor of the other studies for the comparison.

The results for the range of WBAM between our study ([San24]) and the previous studies were:

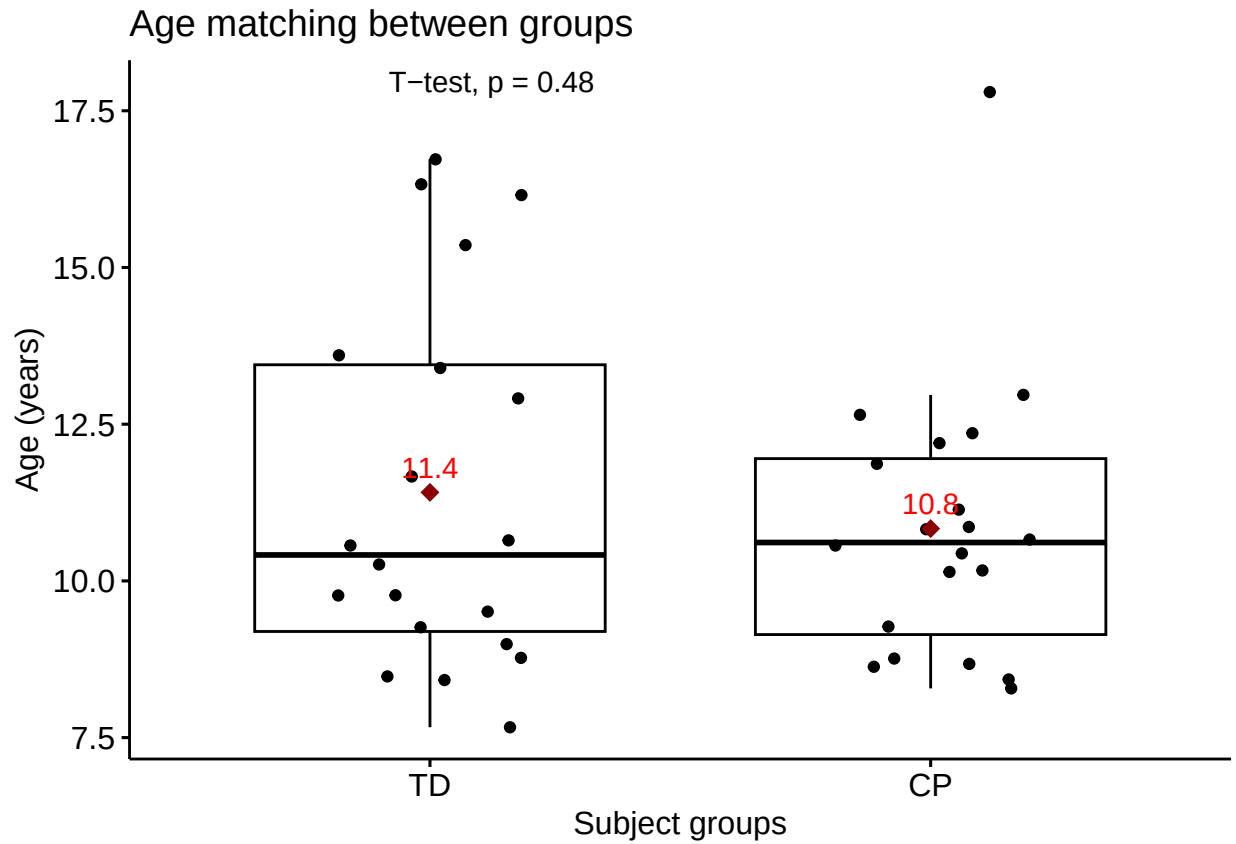
Study	sag.WBAM	cor.WBAM	tra.WBAM
[Her08]	0.0541	0.0340	0.0143
[Rob09]	0.0591	0.0377	0.0115
[Neg23]	0.0634	0.0372	0.0254
[San24]	0.0567	0.0372	0.0172

The results from our study are all within the range of the other studies.

3 Further details for the statistical analysis

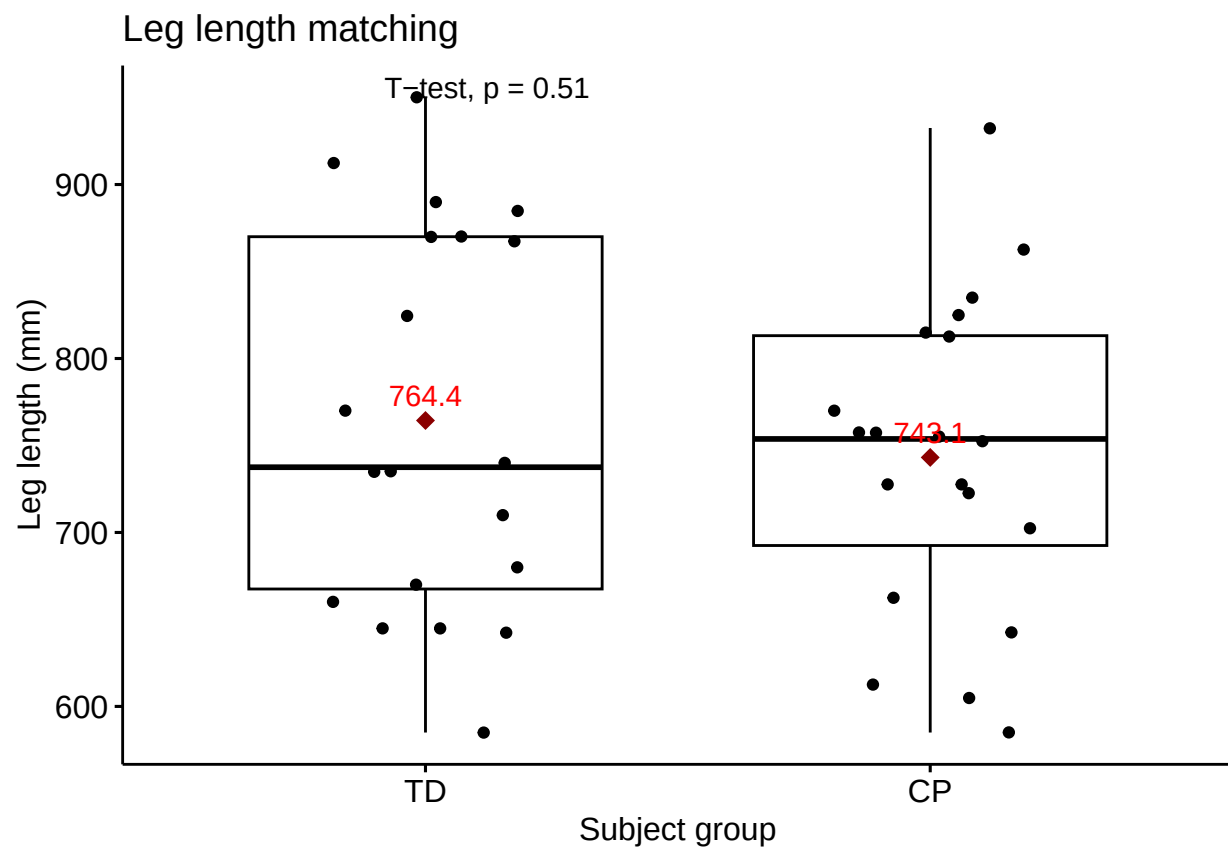
3.1 Check age matching

Age was similar between the two groups.



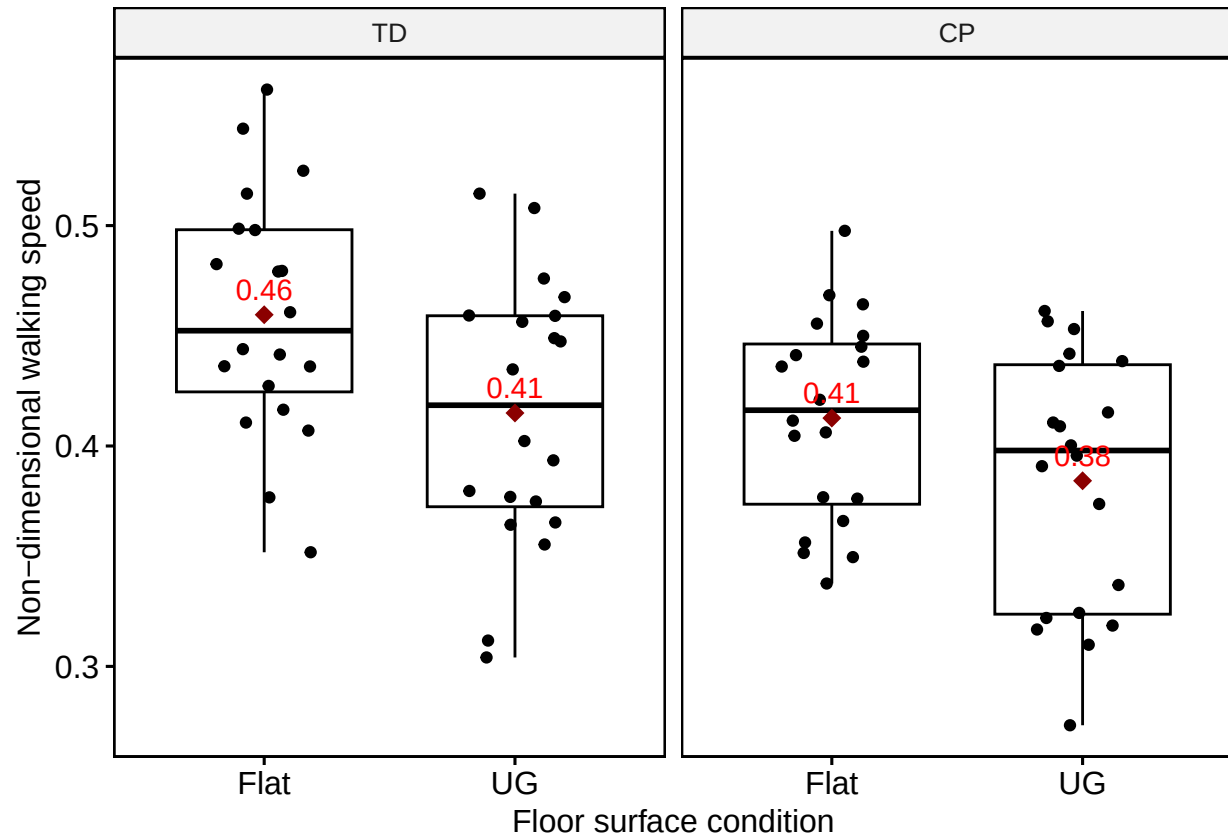
3.2 Check size matching

Leg length was also similar between the two groups.



3.3 Plot walking speed

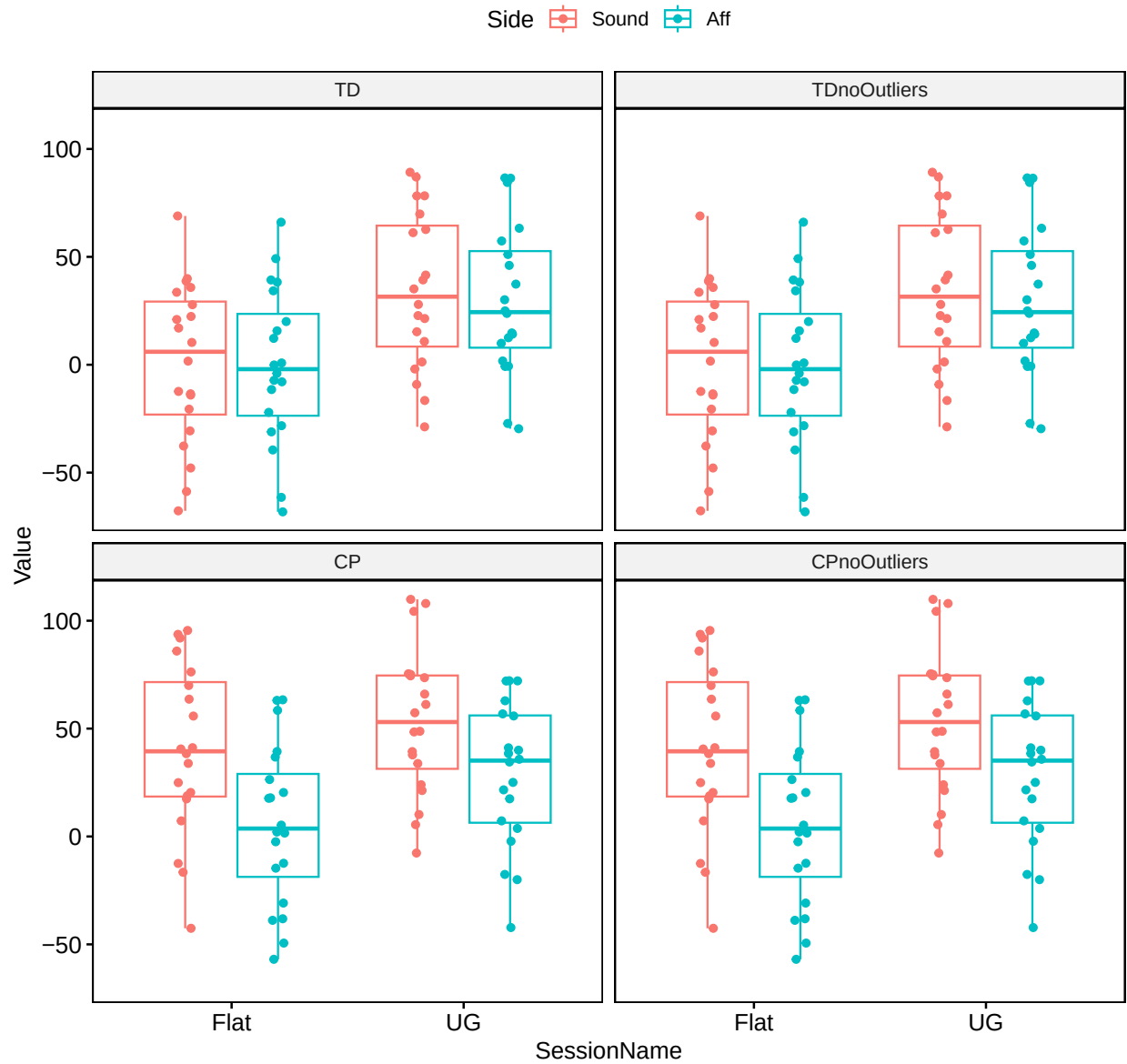
May be interesting to plot dimensionless walking speed to get an idea of the mean values for different conditions.



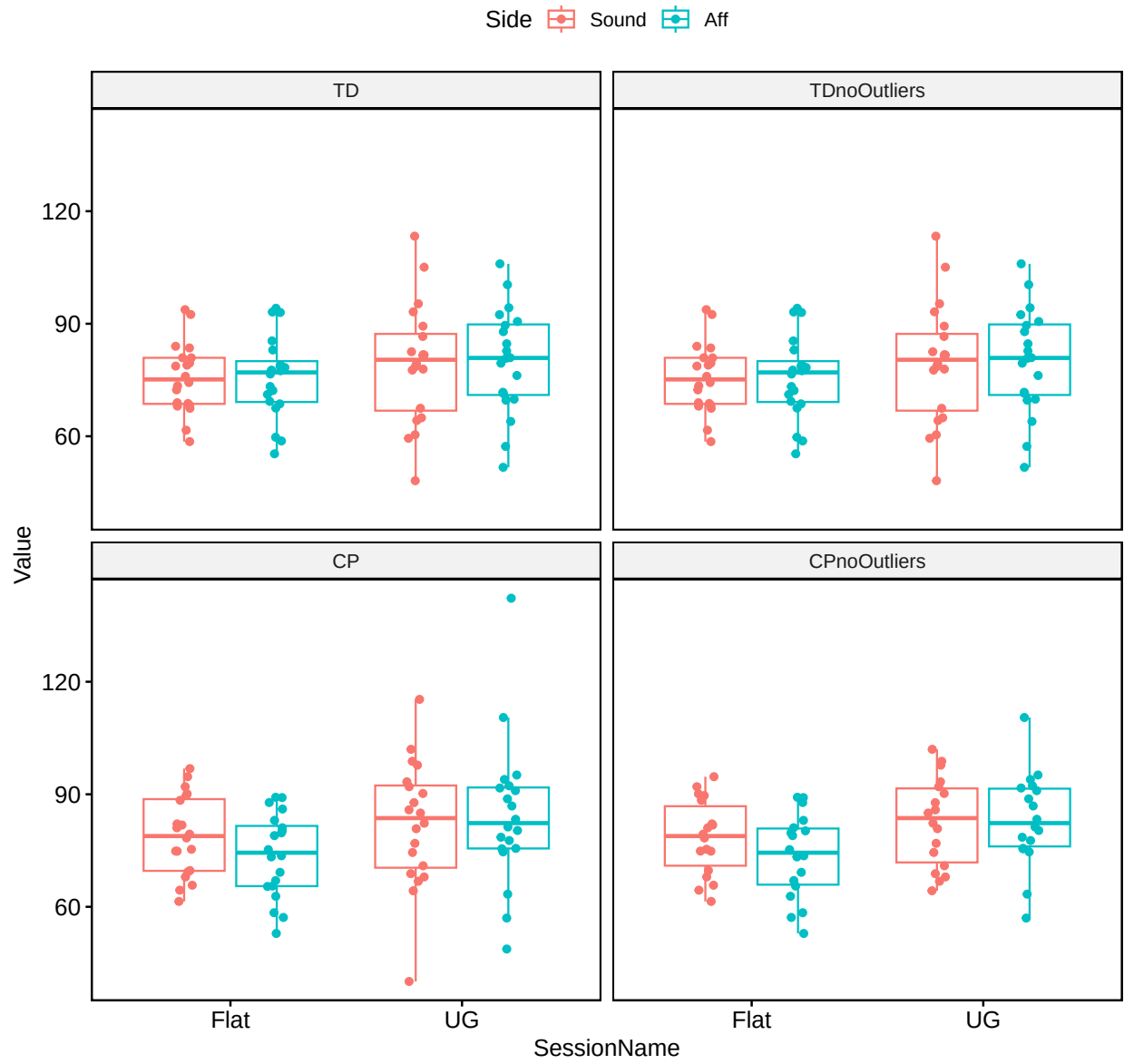
3.4 Plot data for visual checks

The complete dataset is available for visualisation below. Labels of extreme outliers were visually displayed on the graphs for manual checks of the data. The following plots provide a comparison of the dataset with and without outliers to appreciate the (relative absence of) effect of these.

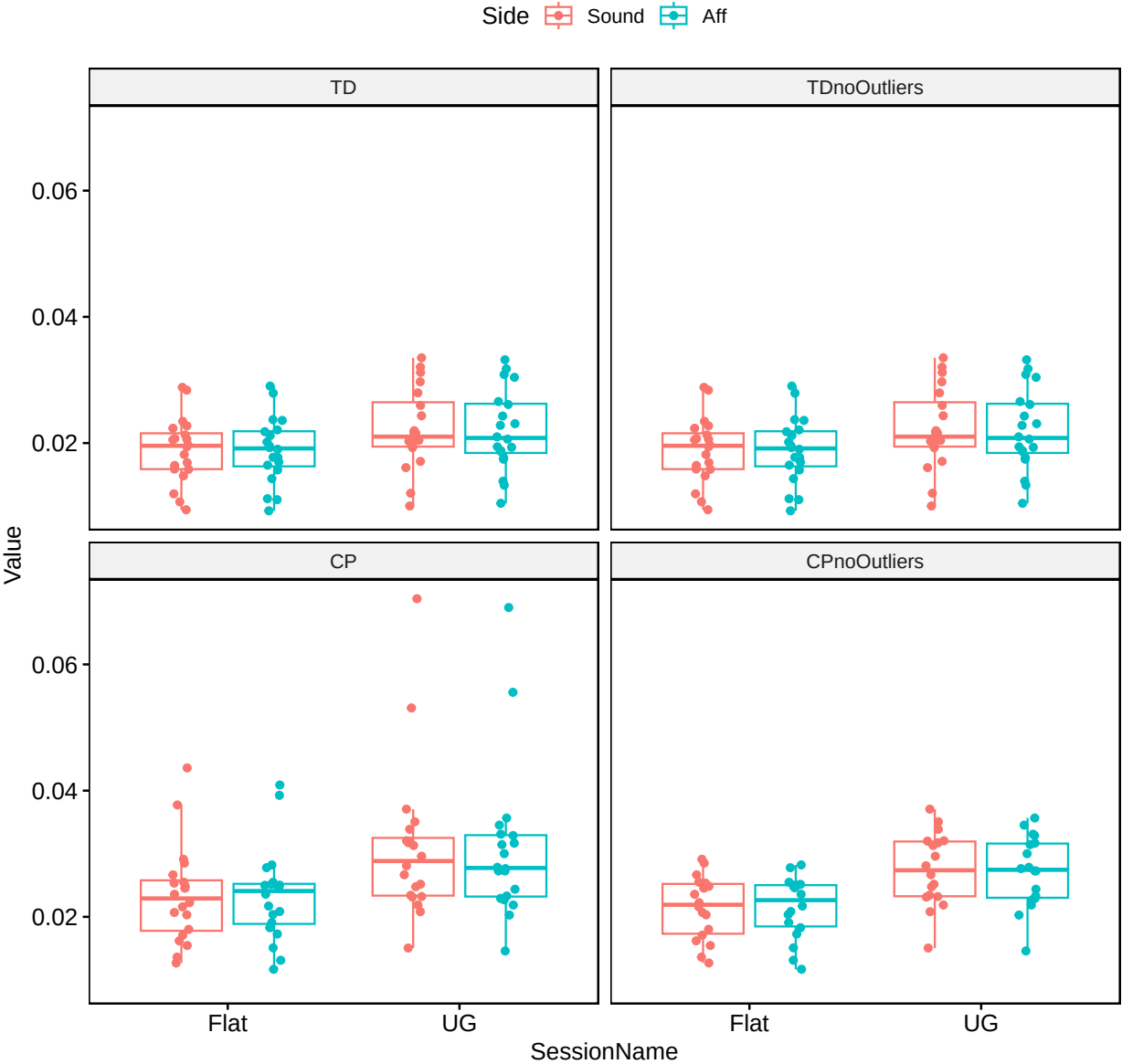
Box plot for variable: Anterior MoS @ footstrike id # 1



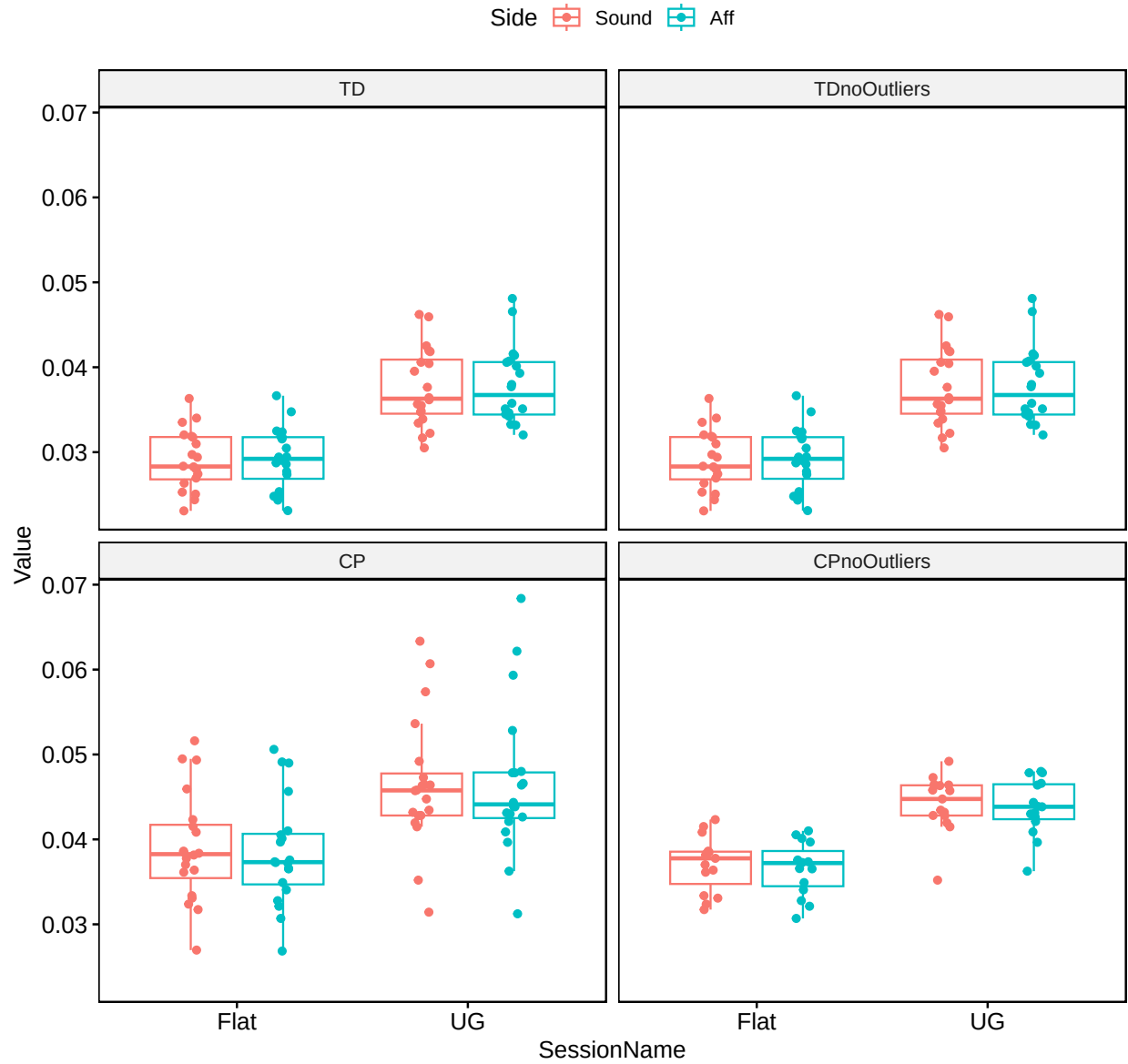
Box plot for variable: Lateral MoS @ footstrike id # 3



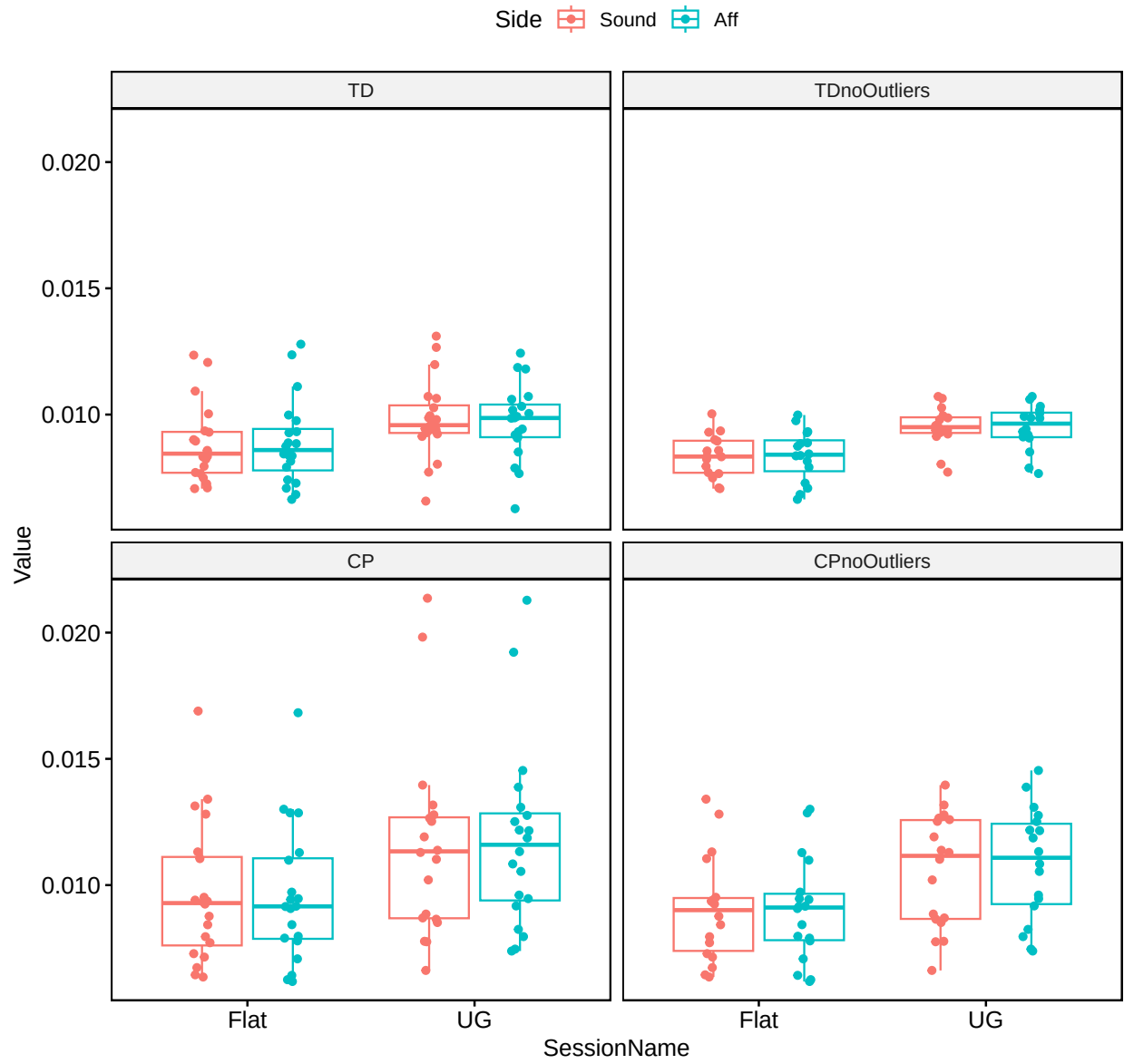
Box plot for variable: Range WBAM frontal plane id # 5



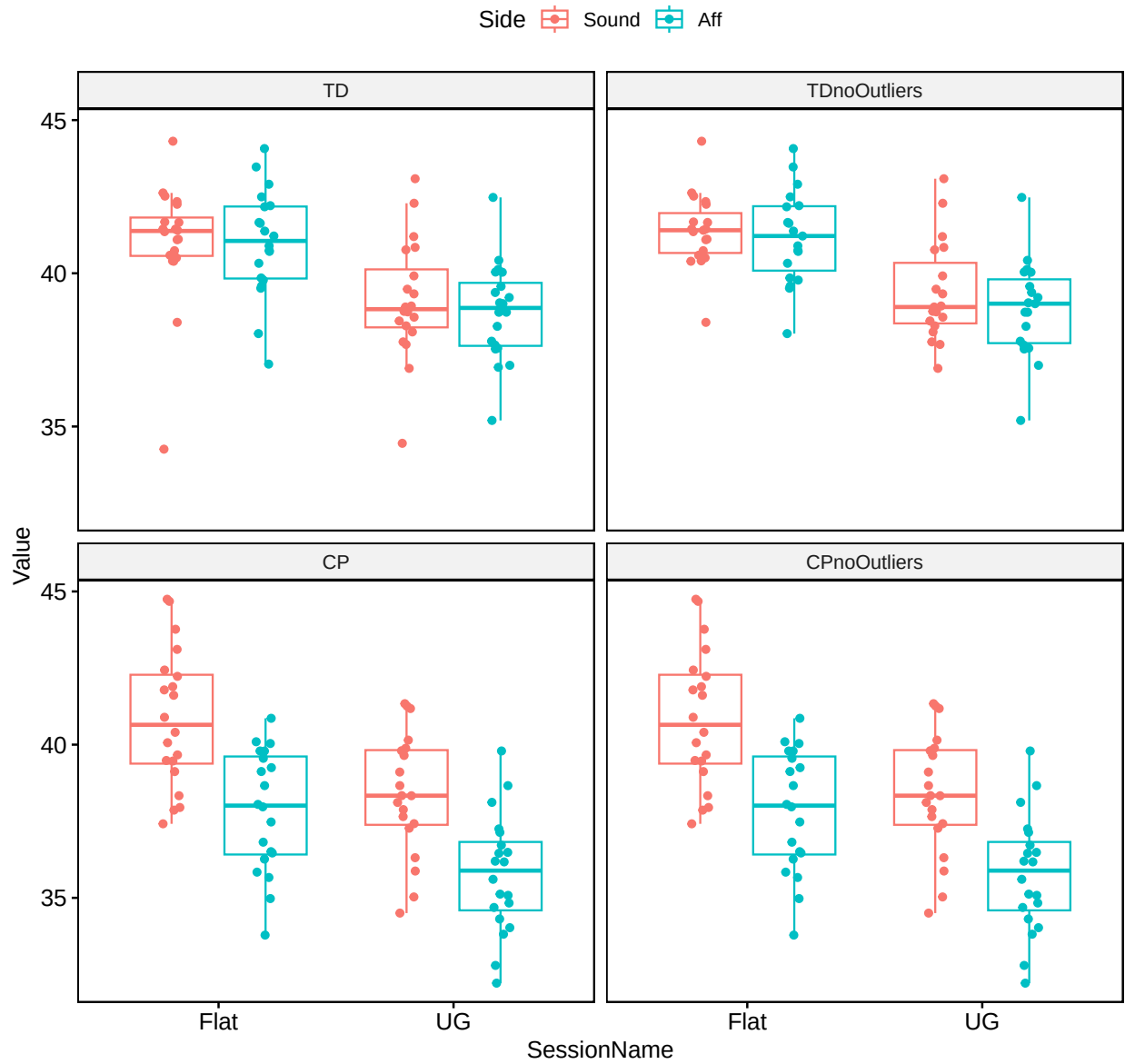
Box plot for variable: Range WBAM sagittal plane id # 6



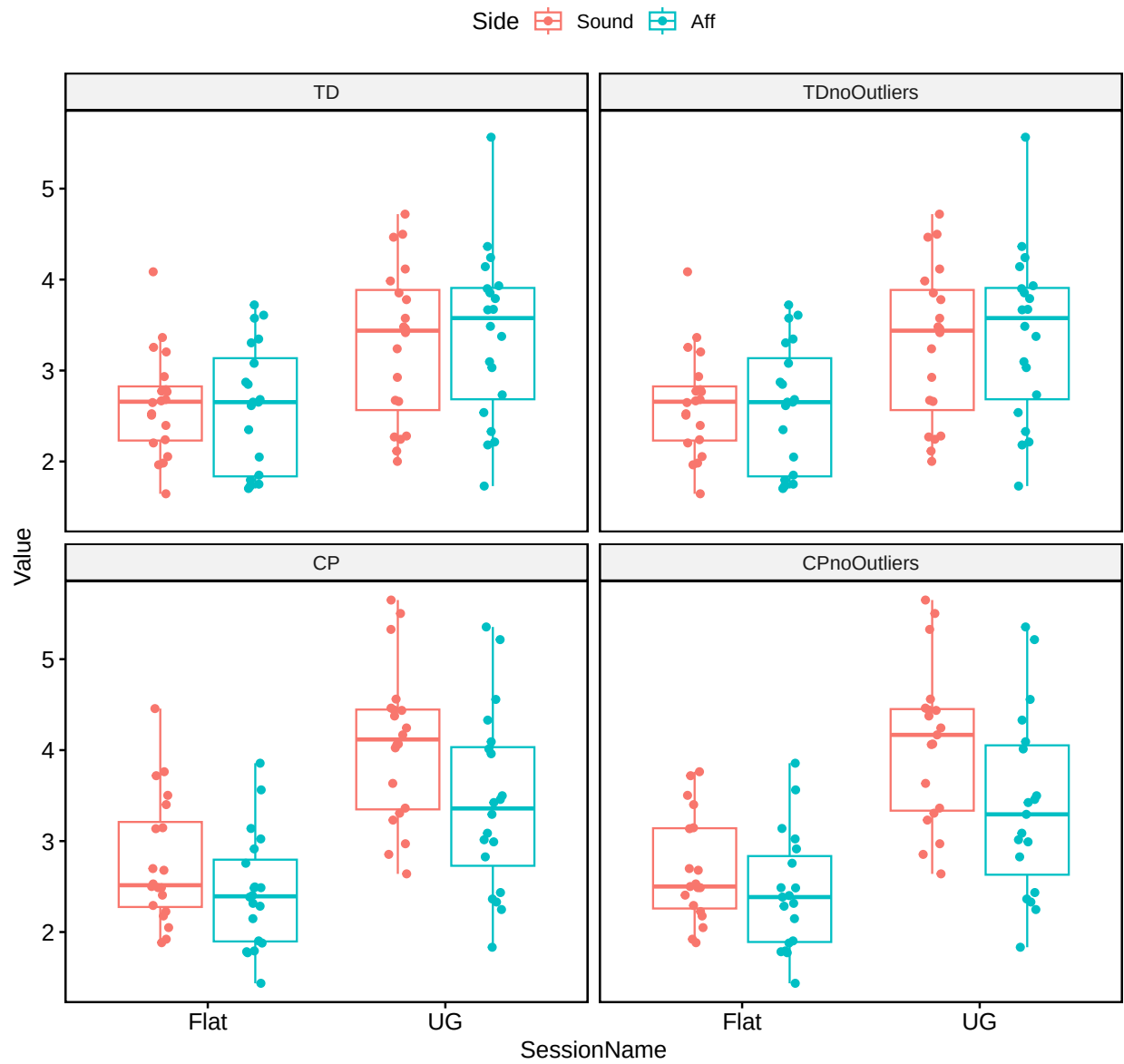
Box plot for variable: Range WBAM transverse plane id # 7



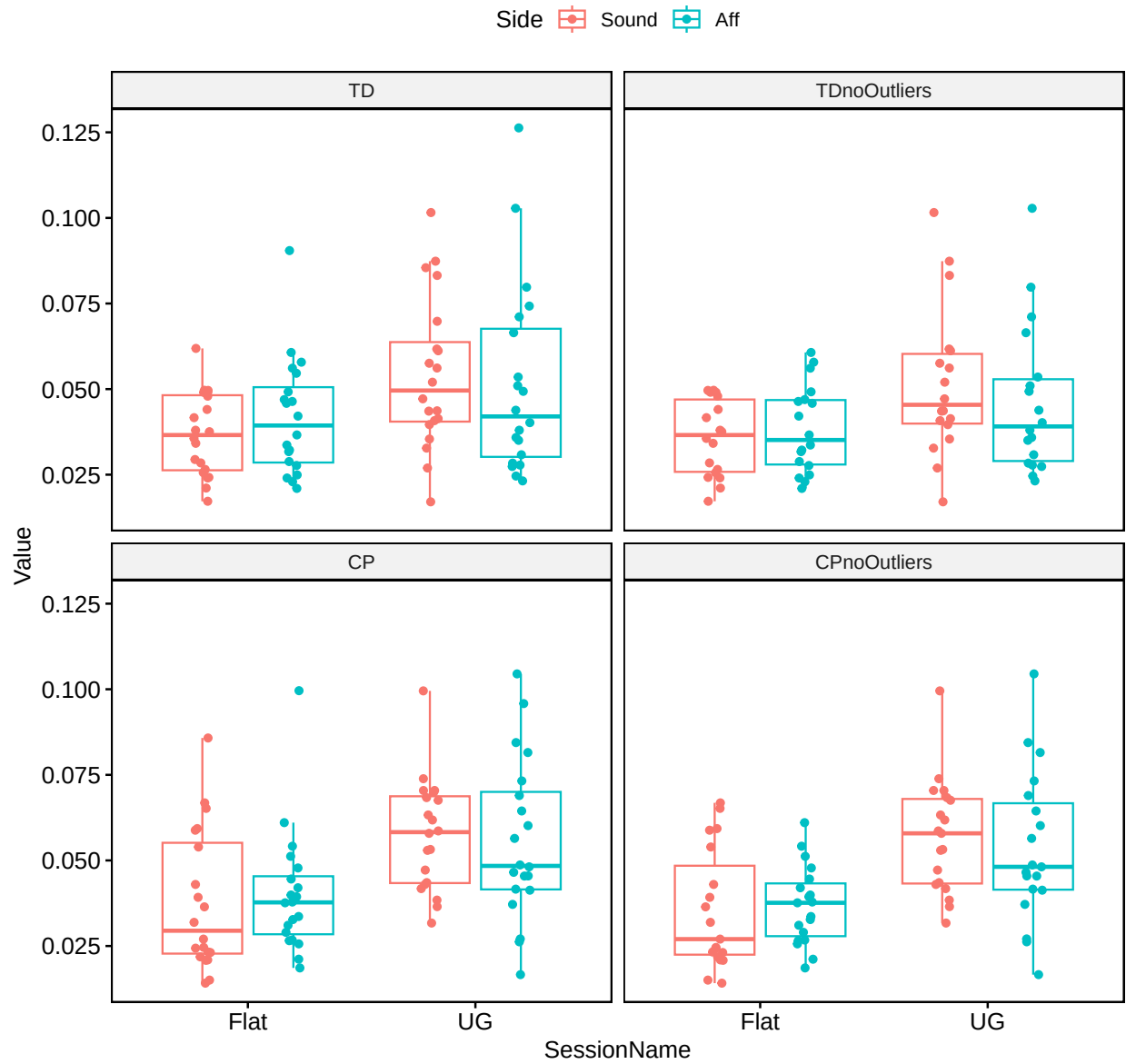
Box plot for variable: ND Single support id # 10



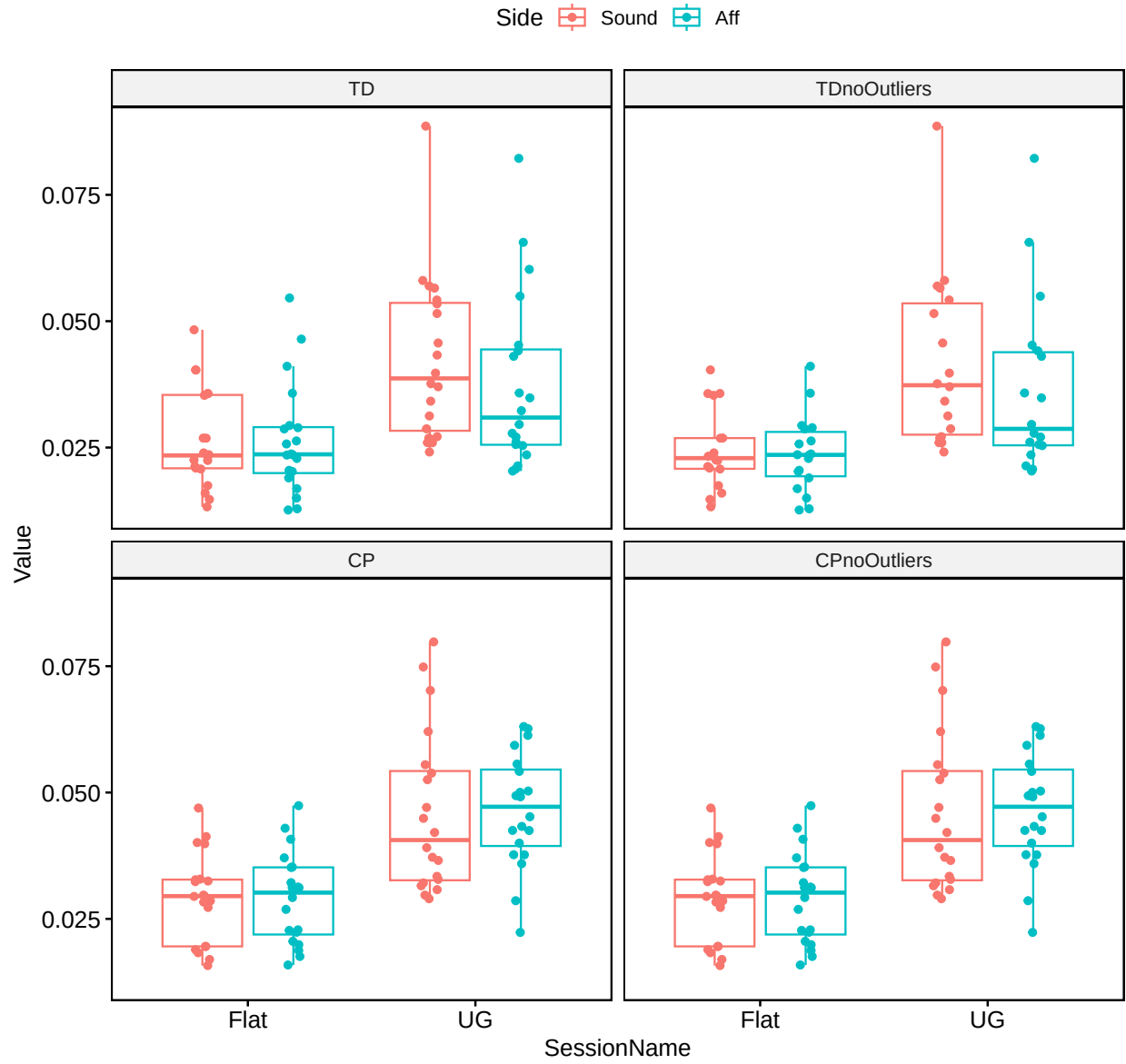
Box plot for variable: Gait SD id # 11



Box plot for variable: SD ND step length id # 17



Box plot for variable: SD ND stride width id # 18



3.5 Mean (SD) values for all indices and walking speed

We provide the mean and standard deviation for all indices for both groups and conditions, as well as walking speed.

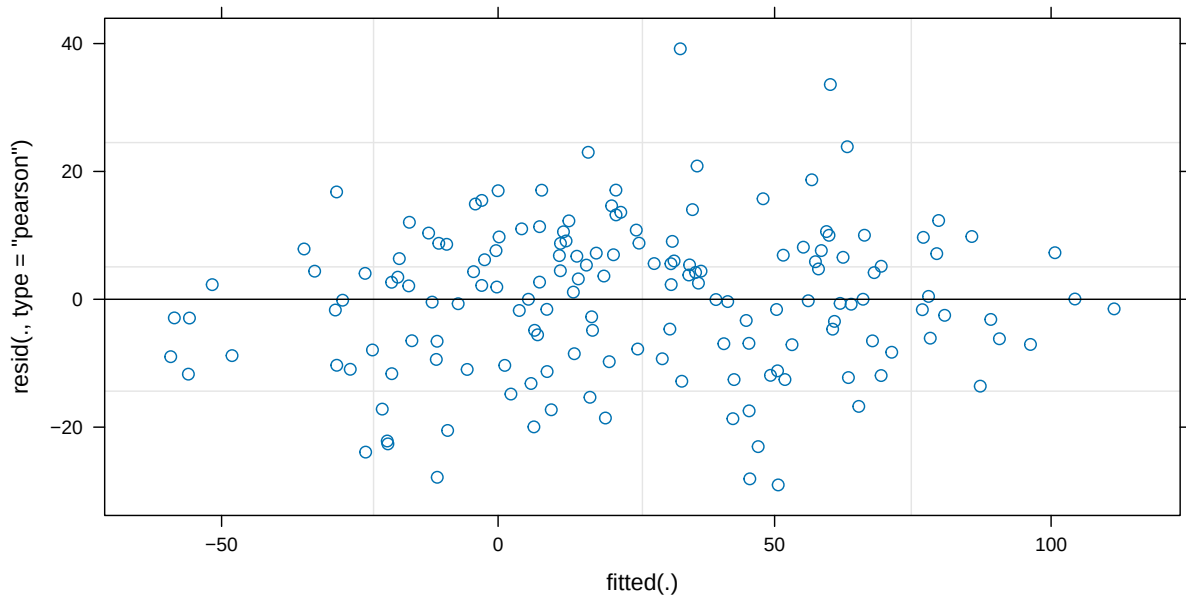
SubjectGroup	SessionName	Side	Walking Speed	ant MoS	lat MoS	cor WBAM	sag WBAM	tra WBAM	Sgl support	GaitSD	step length(SD)	stride width(SD)
TD	Flat	Sound	0.46 (0.055)	0.70 (37)	76 (9.2)	0.019 (0.0051)	0.029 (0.0035)	0.0088 (0.0015)	41 (2.0)	2.6 (0.57)	0.037 (0.012)	0.026 (0.0096)
TD	Flat	Aff	0.46 (0.055)	-0.27 (36)	76 (11)	0.019 (0.0052)	0.029 (0.0036)	0.0089 (0.0017)	41 (1.7)	2.6 (0.70)	0.042 (0.017)	0.026 (0.011)
TD	UG	Sound	0.41 (0.061)	34 (36)	79 (16)	0.022 (0.0063)	0.038 (0.0046)	0.0098 (0.0015)	39 (1.9)	3.3 (0.85)	0.054 (0.022)	0.042 (0.016)
TD	UG	Aff	0.41 (0.060)	29 (35)	80 (14)	0.022 (0.0063)	0.038 (0.0044)	0.0097 (0.0015)	39 (1.6)	3.4 (0.92)	0.051 (0.028)	0.037 (0.017)
CP	Flat	Sound	0.41 (0.046)	40 (39)	79 (11)	0.023 (0.0076)	0.039 (0.0064)	0.0096 (0.0028)	41 (2.2)	2.8 (0.70)	0.038 (0.020)	0.029 (0.0088)
CP	Flat	Aff	0.41 (0.047)	5.4 (37)	74 (11)	0.023 (0.0074)	0.038 (0.0063)	0.0096 (0.0027)	38 (2.0)	2.4 (0.63)	0.040 (0.018)	0.029 (0.0090)
CP	UG	Sound	0.38 (0.058)	53 (34)	82 (17)	0.031 (0.012)	0.046 (0.0077)	0.012 (0.0037)	38 (2.0)	4.1 (0.85)	0.057 (0.016)	0.046 (0.016)
CP	UG	Aff	0.38 (0.055)	29 (33)	84 (20)	0.031 (0.012)	0.047 (0.0087)	0.012 (0.0036)	36 (1.9)	3.4 (0.98)	0.056 (0.023)	0.047 (0.011)

3.6 Statistical modelling

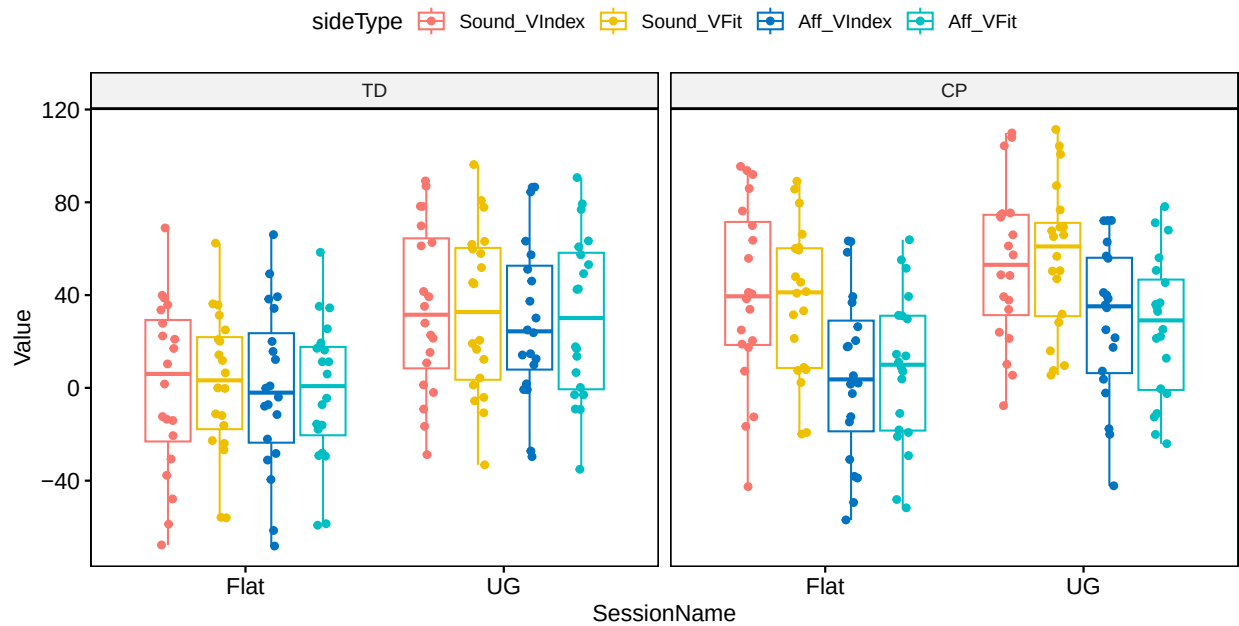
Below are box plots of the data and the fitted data by the statistical model. The fitted model was defined with the following formula:

Value ~ SessionName + SubjectGroup/Side + SessionName:SubjectGroup + WSpeed + (1|SubjectStudyID)

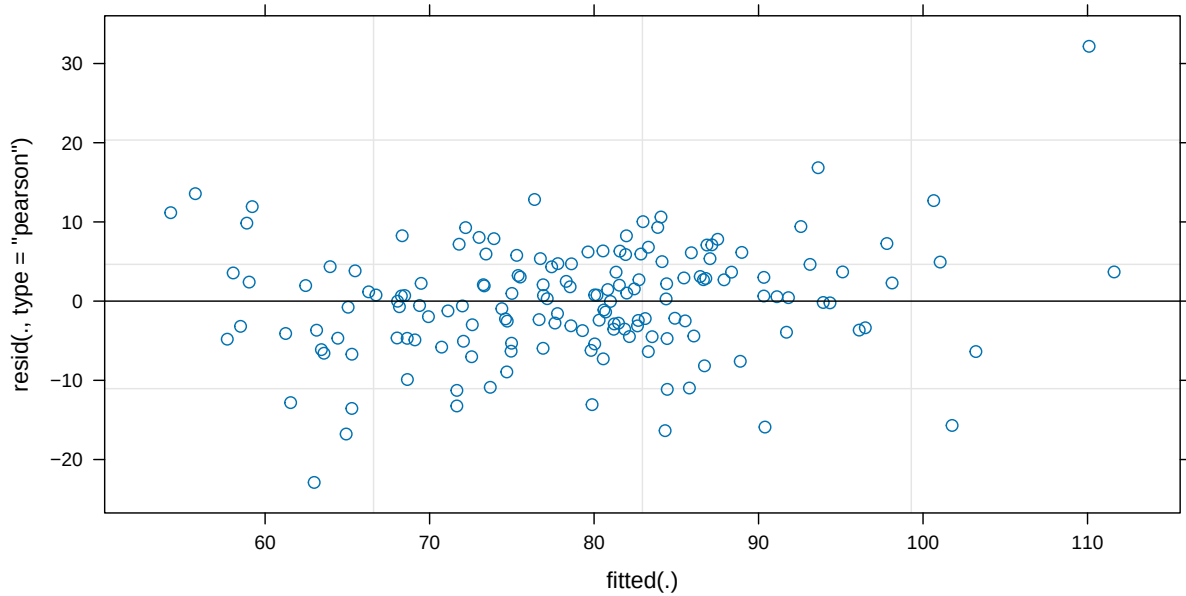
Evaluation plot for variable: Anterior MoS @ footstrike id # 1



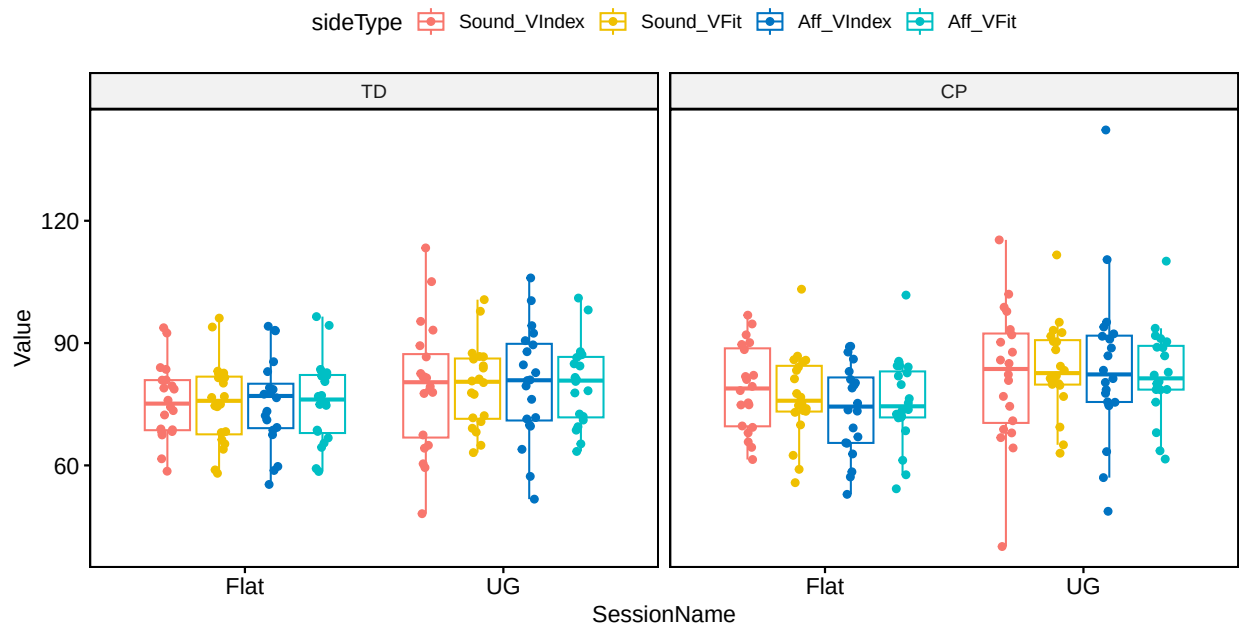
Box plot for variable: Anterior MoS @ footstrike id # 1



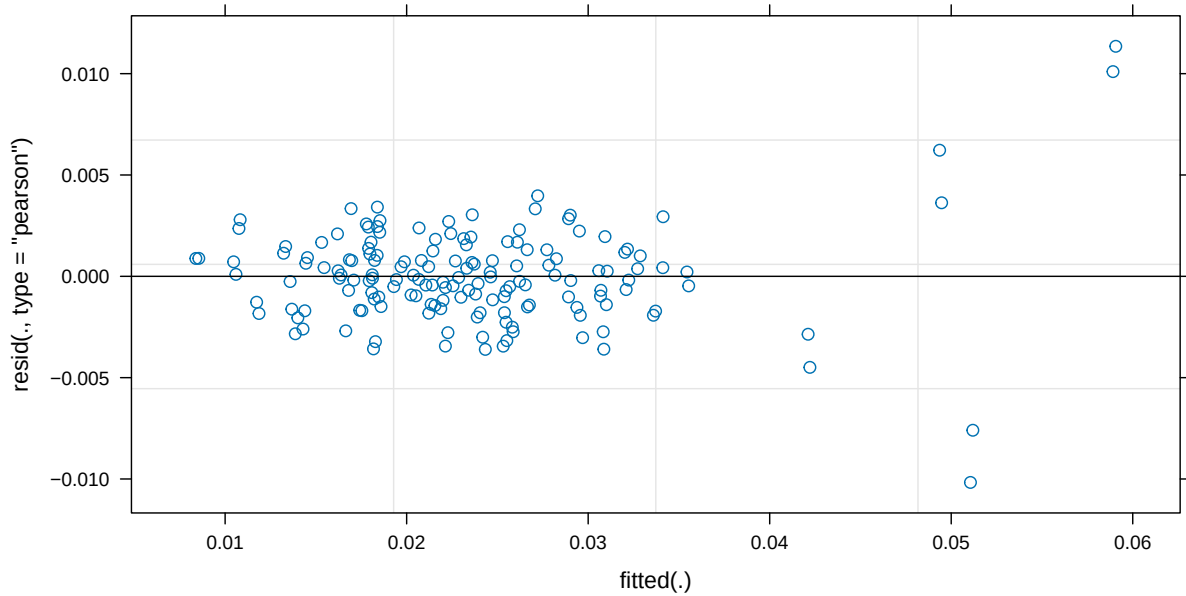
Evaluation plot for variable: Lateral MoS @ footstrike id # 3



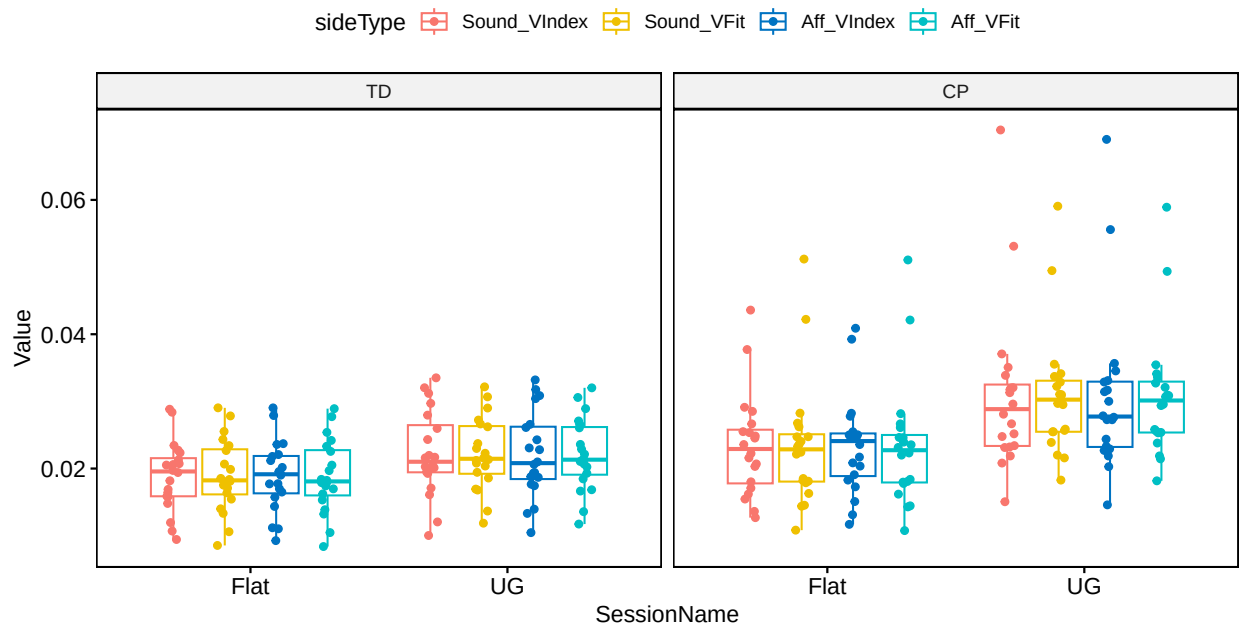
Box plot for variable: Lateral MoS @ footstrike id # 3



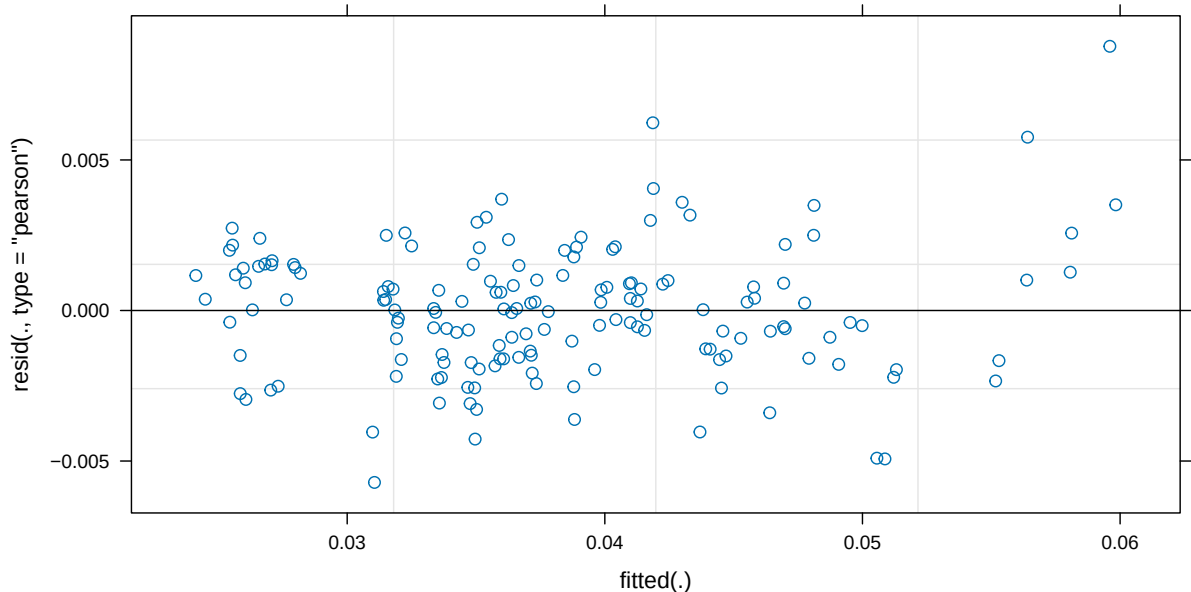
Evaluation plot for variable: Range WBAM frontal plane id # 5



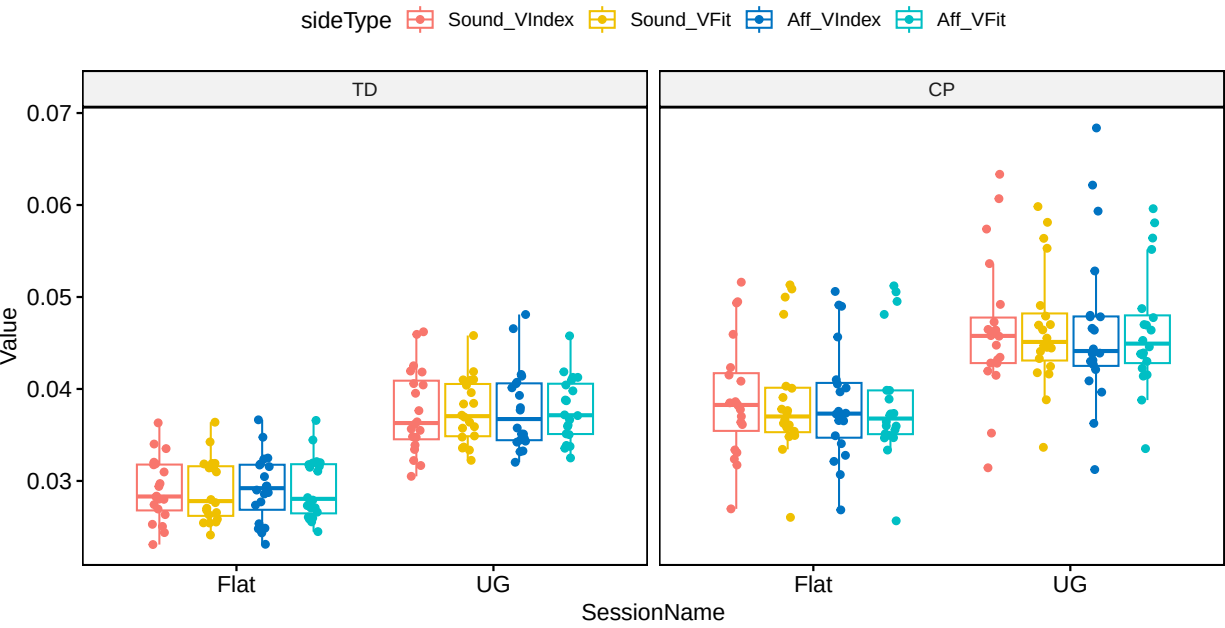
Box plot for variable: Range WBAM frontal plane id # 5



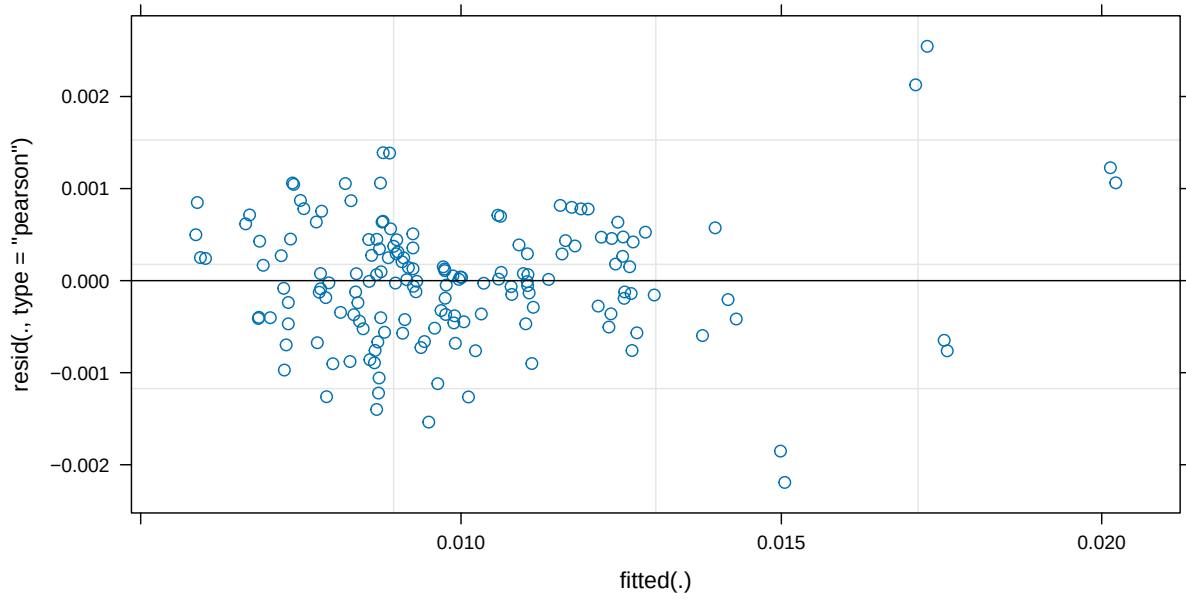
Evaluation plot for variable: Range WBAM sagittal plane id # 6



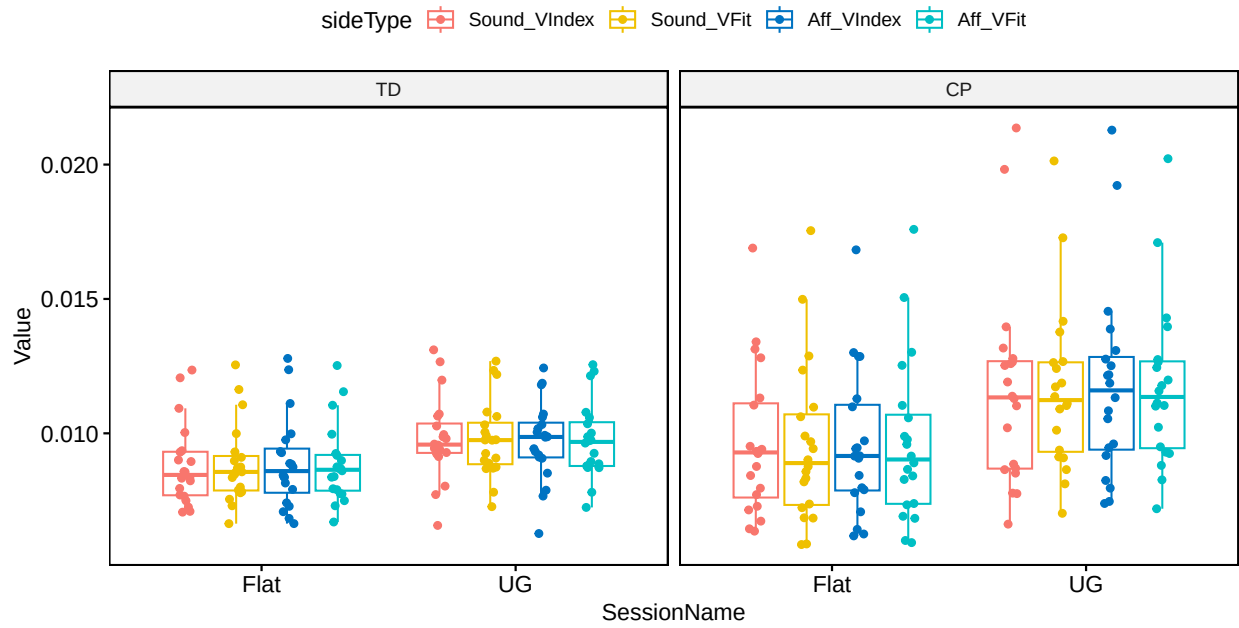
Box plot for variable: Range WBAM sagittal plane id # 6



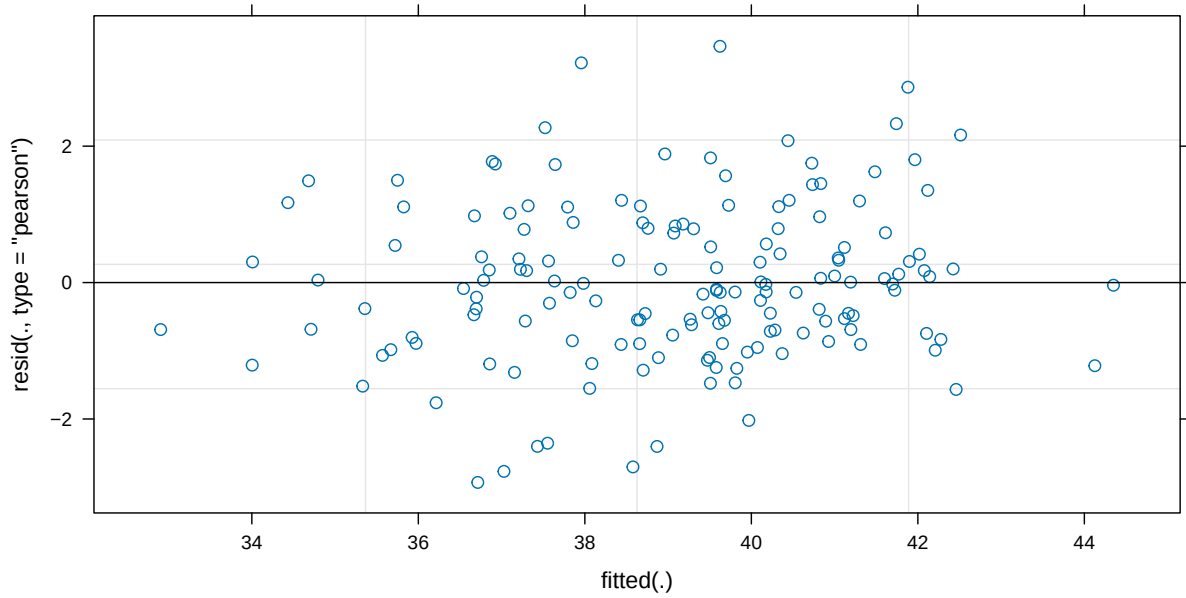
Evaluation plot for variable: Range WBAM transverse plane id # 7



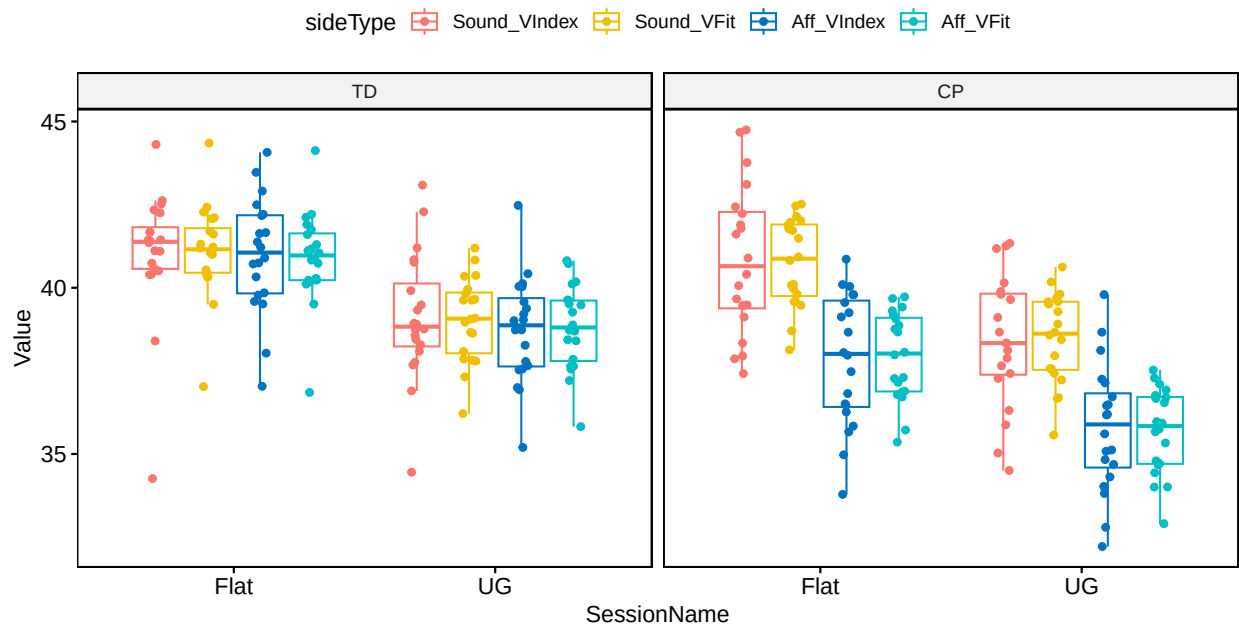
Box plot for variable: Range WBAM transverse plane id # 7



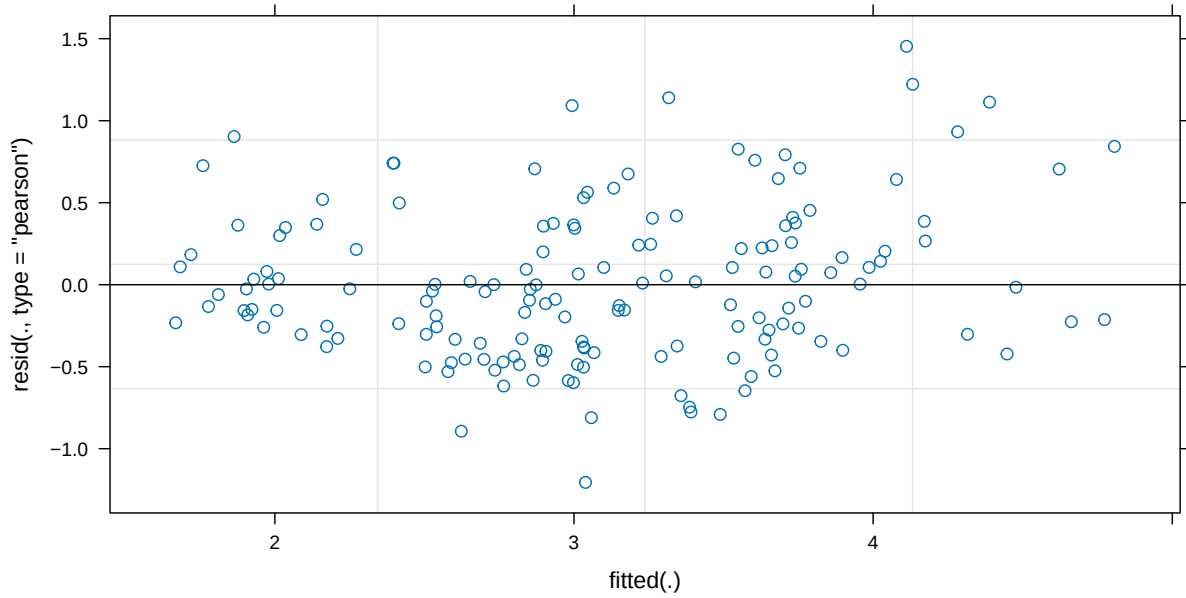
Evaluation plot for variable: ND Single support id # 10



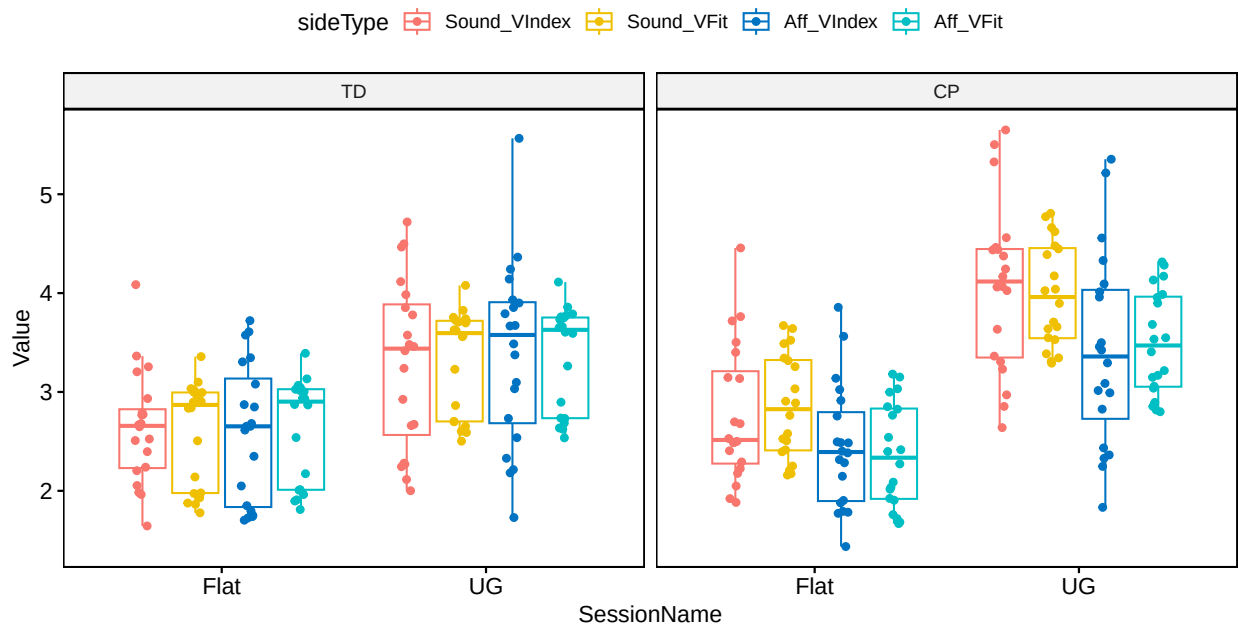
Box plot for variable: ND Single support id # 10



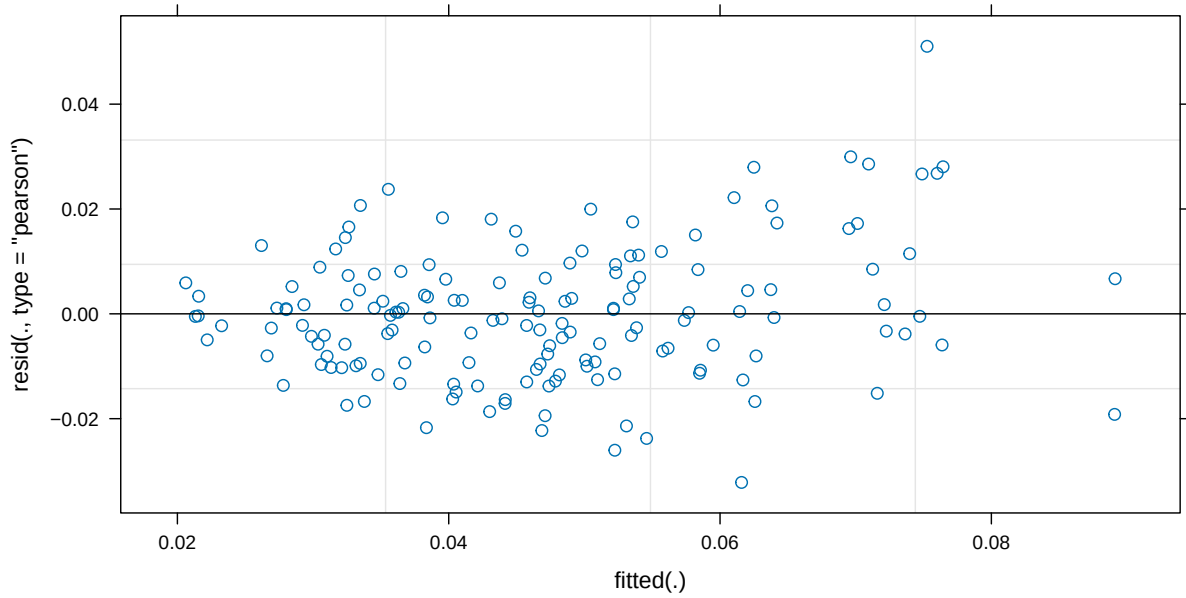
Evaluation plot for variable: Gait SD id # 11



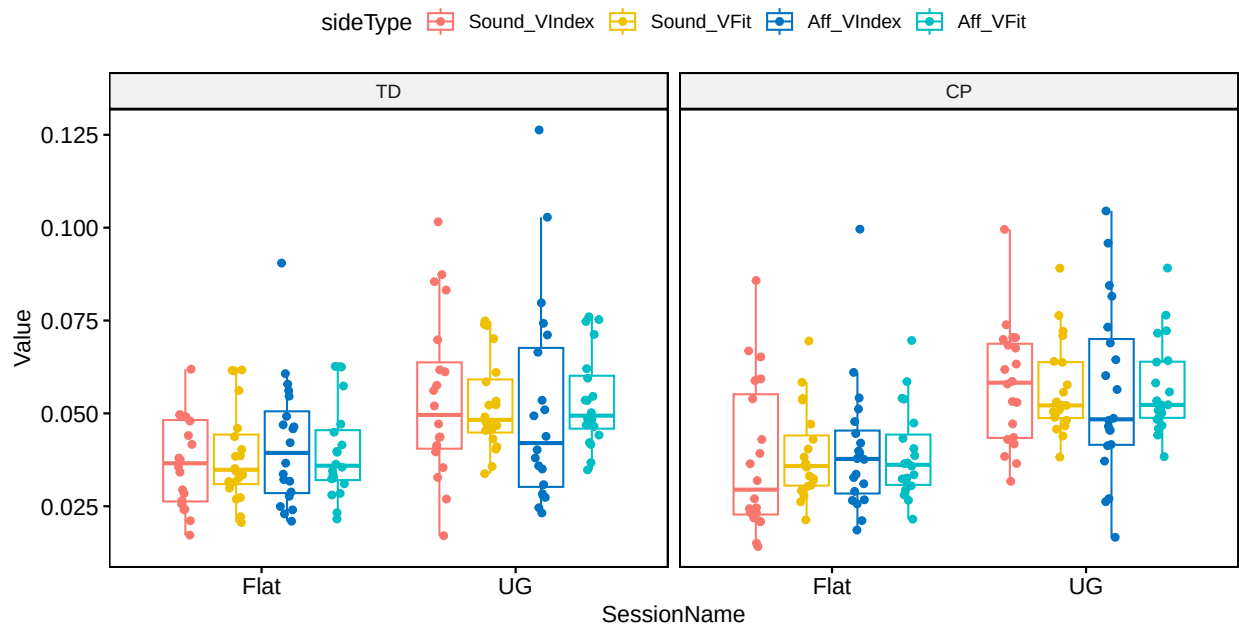
Box plot for variable: Gait SD id # 11



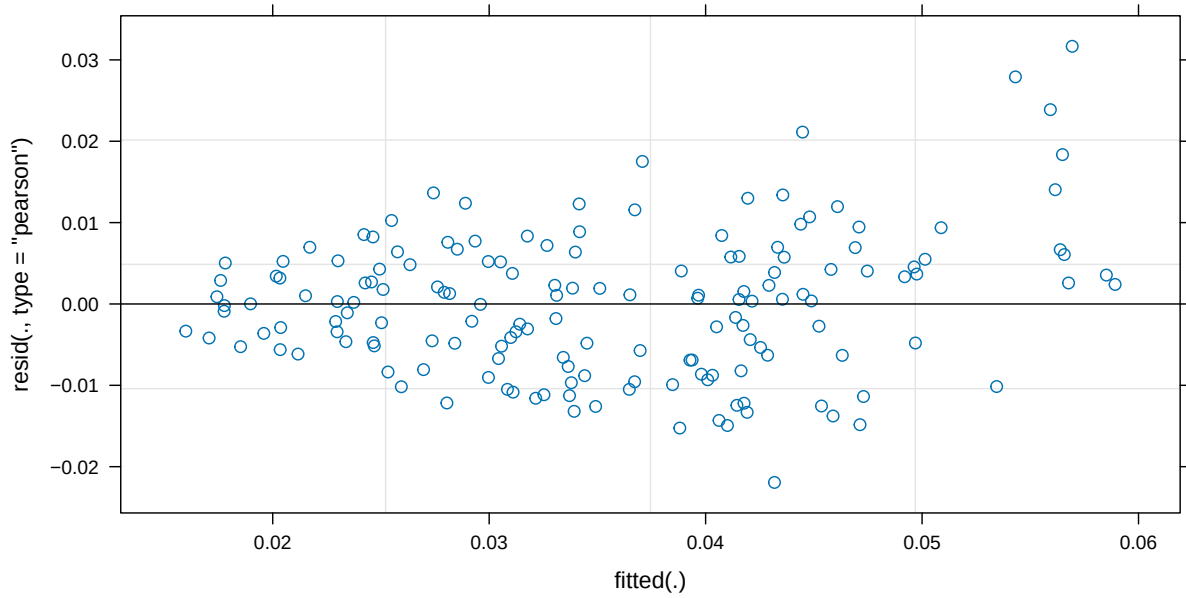
Evaluation plot for variable: SD ND step length id # 17



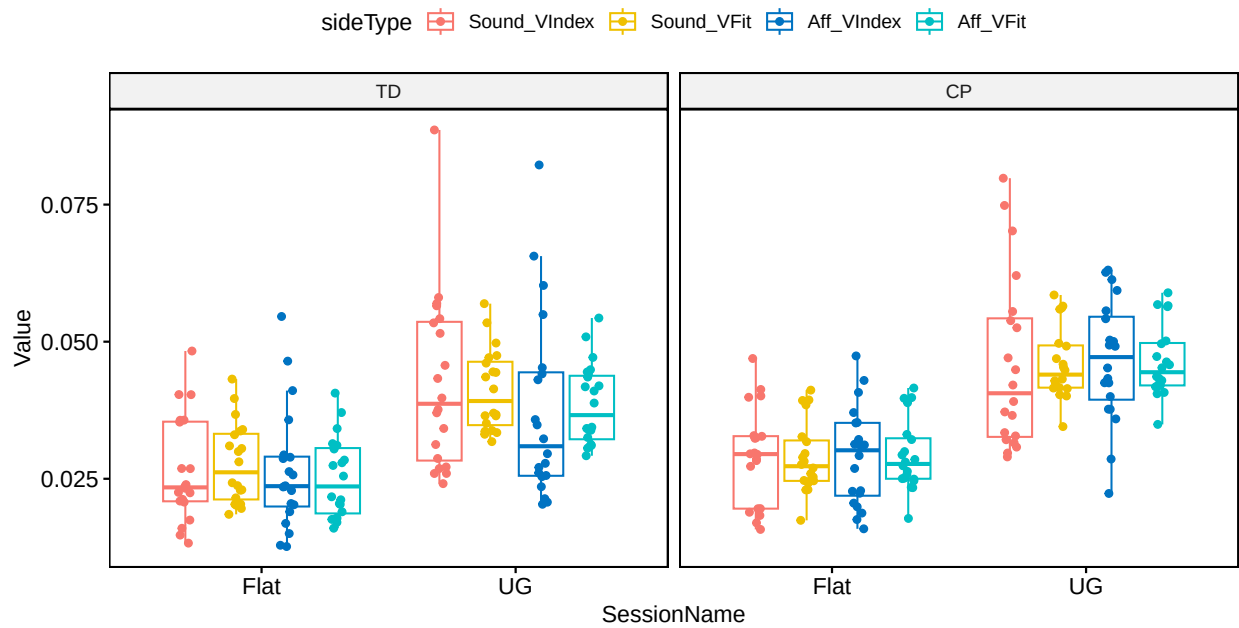
Box plot for variable: SD ND step length id # 17



Evaluation plot for variable: SD ND stride width id # 18



Box plot for variable: SD ND stride width id # 18



3.7 Table of the model estimates

term	ant MoS	lat MoS	cor WBAM	sag WBAM	tra WBAM	Sgl support	GaitSD	step length(SD)	stride width(SD)
(Intercept)	251.7***	83.1***	0.02***	0.02***	0.003*	31.3***	2.6***	0.05**	0.02*
SessionNameUG	6.8*	3.4	0.003***	0.010***	0.002***	-1.1***	0.7***	0.01***	0.01***
SubjectGroupCP	10.0	0.9	0.004	0.01***	0.001	0.7	0.3	-9e-04	0.001
WSpeed	-543.3***	-16.8	-0.005	0.03***	0.01***	21.4***	-0.06	-0.02	0.006
SubjectGroupTD:SideAff	-3.4	0.4	-1e-04	2e-04	-1e-05	-0.2	0.03	0.001	-0.003
SubjectGroupCP:SideAff	-30.1***	-1.4	-1e-04	-2e-04	1e-04	-2.8***	-0.5***	2e-04	4e-04
SessionNameUG:SubjectGroupCP	-3.7	3.0	0.004***	-0.001	9e-04***	-0.6	0.4*	0.004	0.004

Walking speed had a huge effect on the anterior MoS. We propose the following interpretation of the estimated coefficient for walking speed.

Walking speed was made non-dimensional before analysis so it is necessary to correct any walking speed value in m/s by a factor of $\sqrt{(g \times l_0)}$ where g is the acceleration of gravity and l_0 the characteristic length (leg length). This would mean that a difference in walking speed of 1m/s should be seen as a change in non-dimensional walking speed of 0.37 for a leg length of 0.75m (approximately the average leg length for both groups).

For interpretation, we may use the mean differences in non-dimensional walking speed between conditions to appreciate the effect. For example, walking speed was 0.46 (TD, flat) vs 0.41 (TD, UG) $\rightarrow$ 0.05 difference $\rightarrow$ 0.05 x -543.3 = -27mm.

The interpretation would then be: there was a mean predicted change in anterior MoS due to walking speed alone of -27mm between floor conditions in TD. This may then be compared with the estimated effect of the sole UG condition on the anterior MoS: -6.8mm (Table 2). As a result, the mean effect of the change in non-dimensional walking speed between floor conditions in TD is about $27/6.8 = 4$ times larger than the sole effect of the uneven ground itself.

3.8 Alternative computations for the MoS

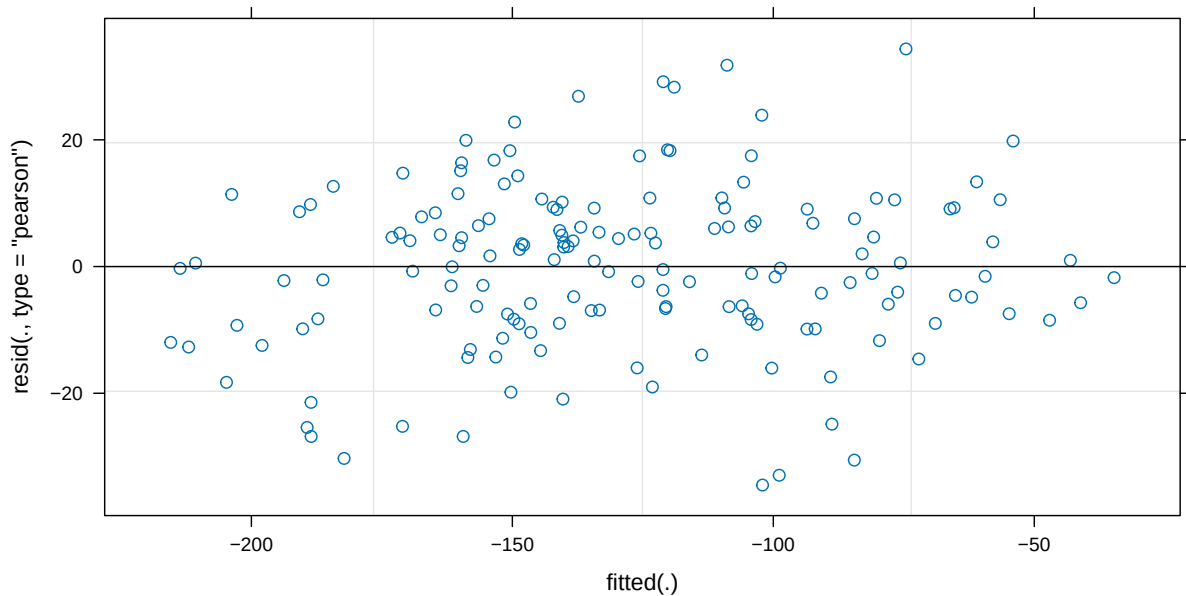
3.8.1 Using the HEE instead of the TOE marker

Let's try to use a different marker on the foot to define the boundary of support. This time with the HEE marker instead of the TOE marker.

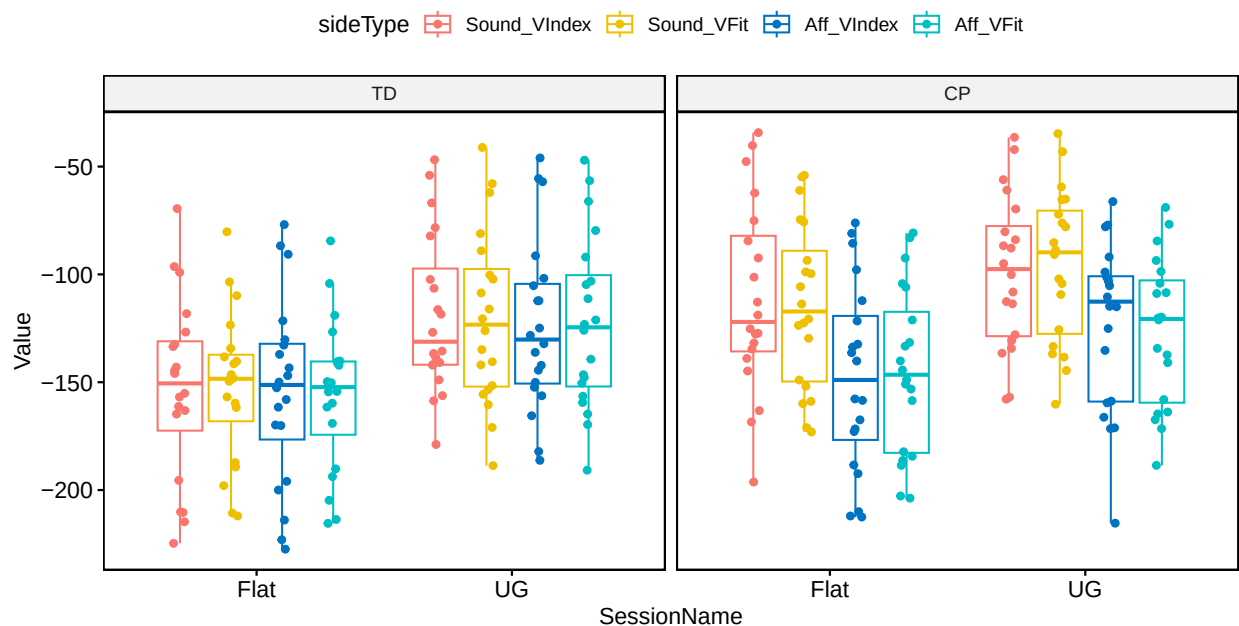
Below are box plots of the data and the fitted data by the statistical model. The fitted model was defined with the following formula:

Value ~ SessionName + SubjectGroup/Side + SessionName:SubjectGroup + WSpeed + (1|SubjectStudyID)

Evaluation plot for variable: Anterior MoS @ footstrike id # 1



Box plot for variable: Anterior MoS @ footstrike id # 1



3.8.2 New table of the model estimates

term	ant MoS
(Intercept)	106.3***
SessionNameUG	6.8
SubjectGroupCP	11.0
WSpeed	-562.1***
SubjectGroupTD:SideAff	-3.6
SubjectGroupCP:SideAff	-31.0***
SessionNameUG:SubjectGroupCP	-3.9

Using the TOE or HEE marker did not have a major impact on the results, beyond the intercept. The p value for the effect of floor condition used to be below the cut off of 0.05 but is now 0.08 (although the estimate has not changed at 6.8).

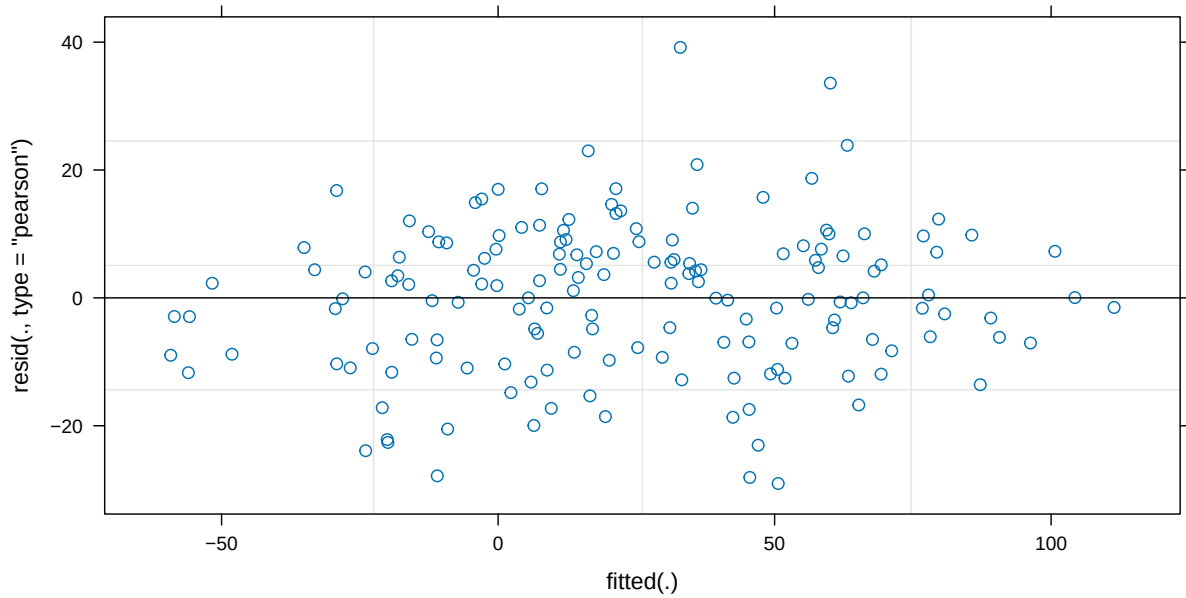
3.8.3 MoS not based on timing (footstrike) but maximum

The MoS may be calculated at any point in time. The moment of foot contact is the preferred choice in the literature by far, since it is the moment that more or less determines foot placement for the stance phase. However, one may be interested in the maximum value of the MoS at any point during the gait cycle.

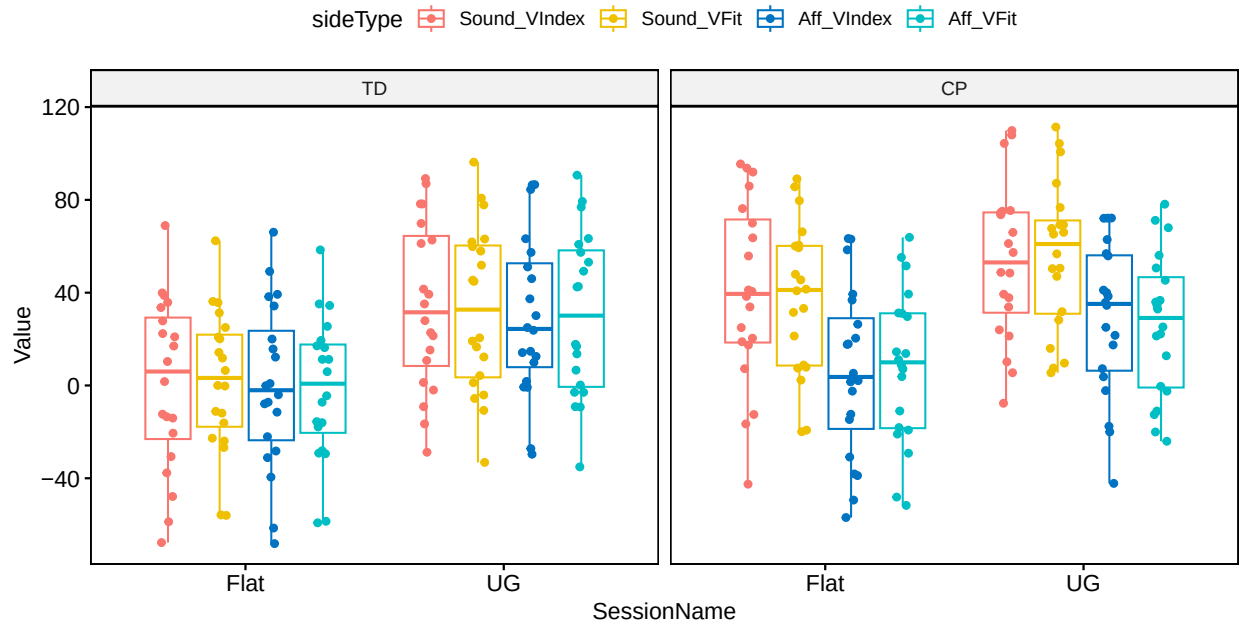
Below are box plots of the data and the fitted data by the statistical model. The fitted model was defined with the following formula:

Value ~ SessionName + SubjectGroup/Side + SessionName:SubjectGroup + WSpeed + (1|SubjectStudyID)

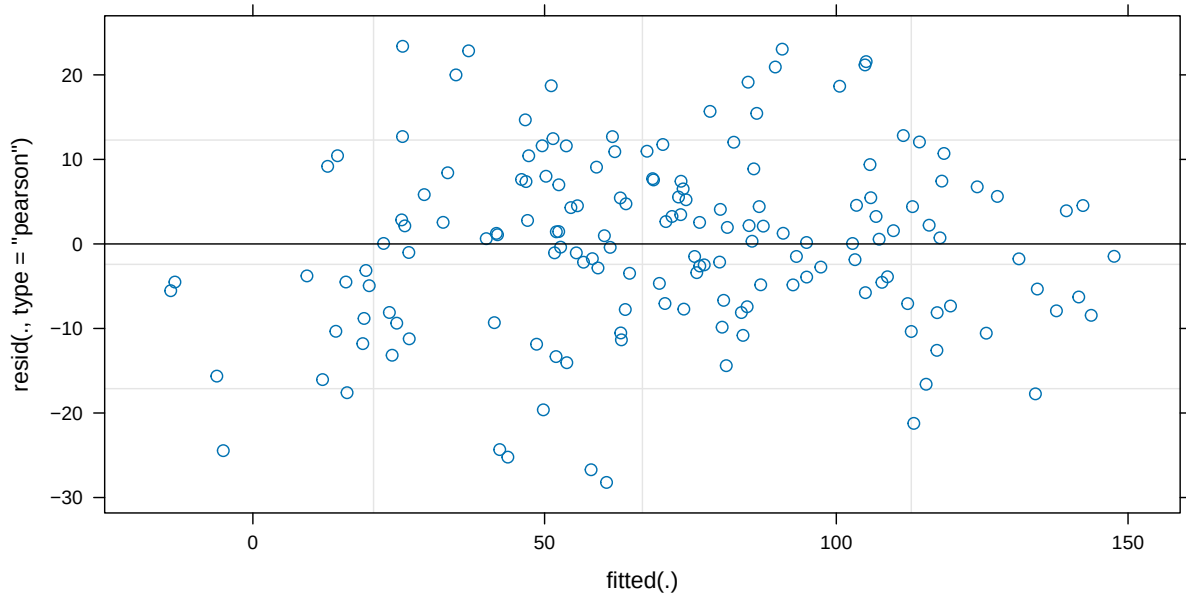
Evaluation plot for variable: Anterior MoS @ footstrike id # 1



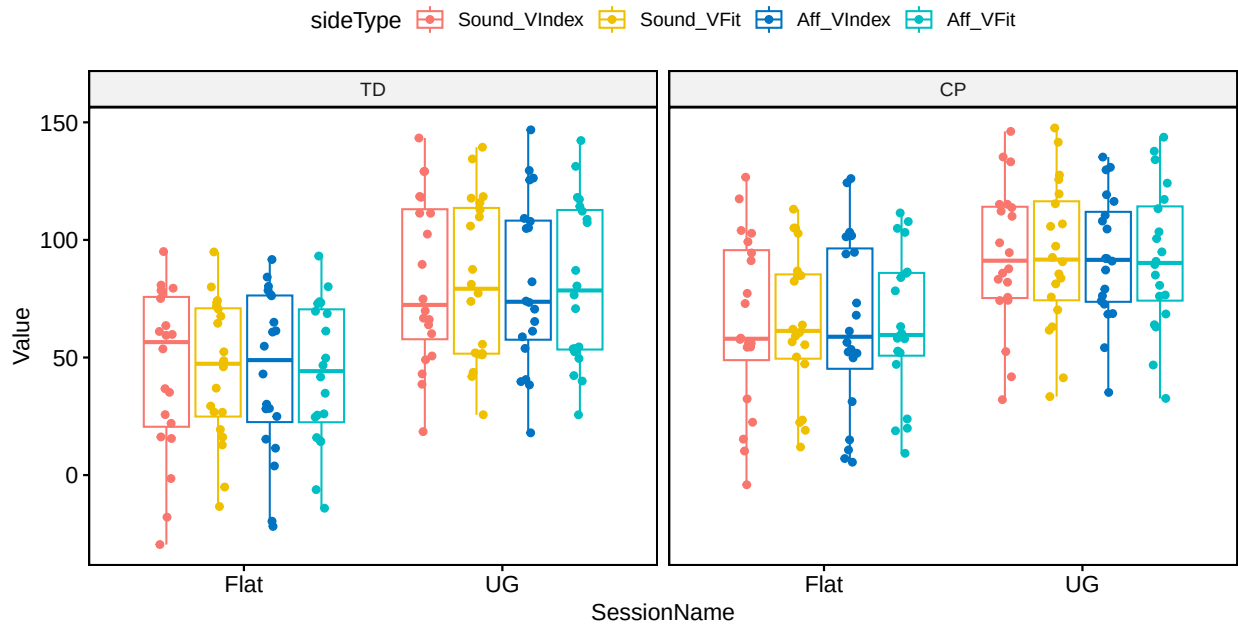
Box plot for variable: Anterior MoS @ footstrike id # 1



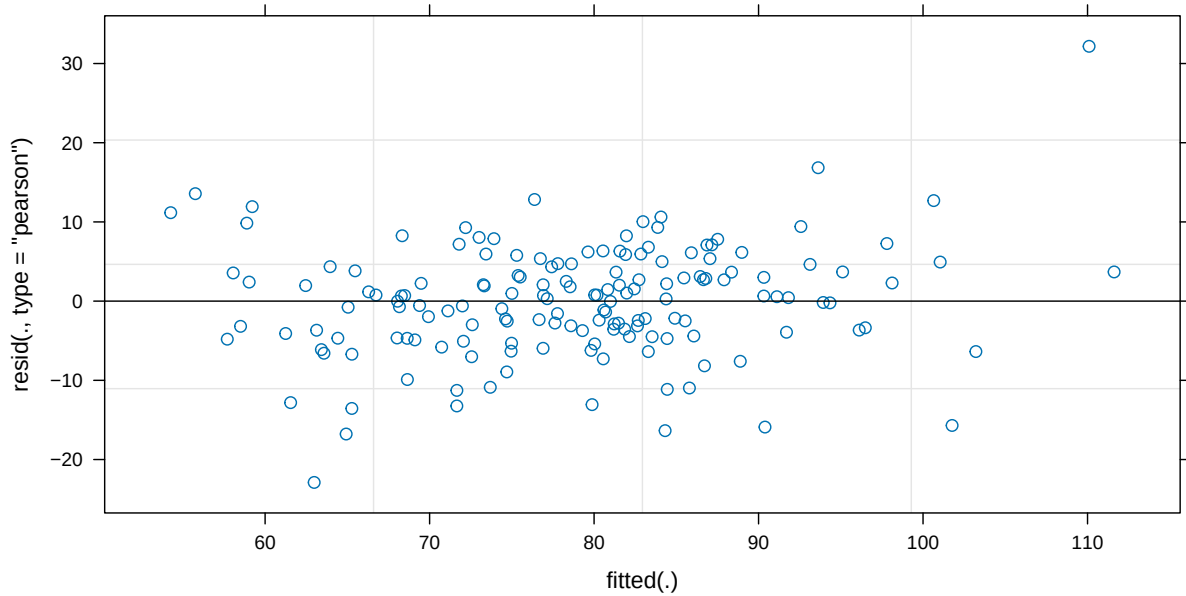
Evaluation plot for variable: Maximum anterior MoS id # 2



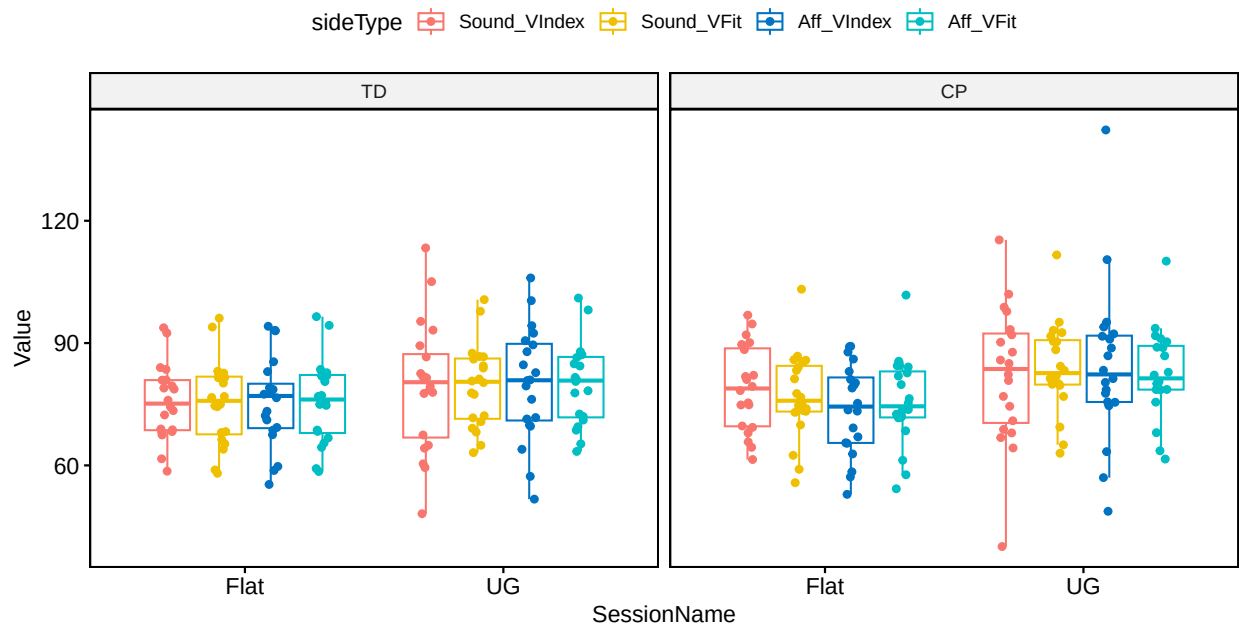
Box plot for variable: Maximum anterior MoS id # 2



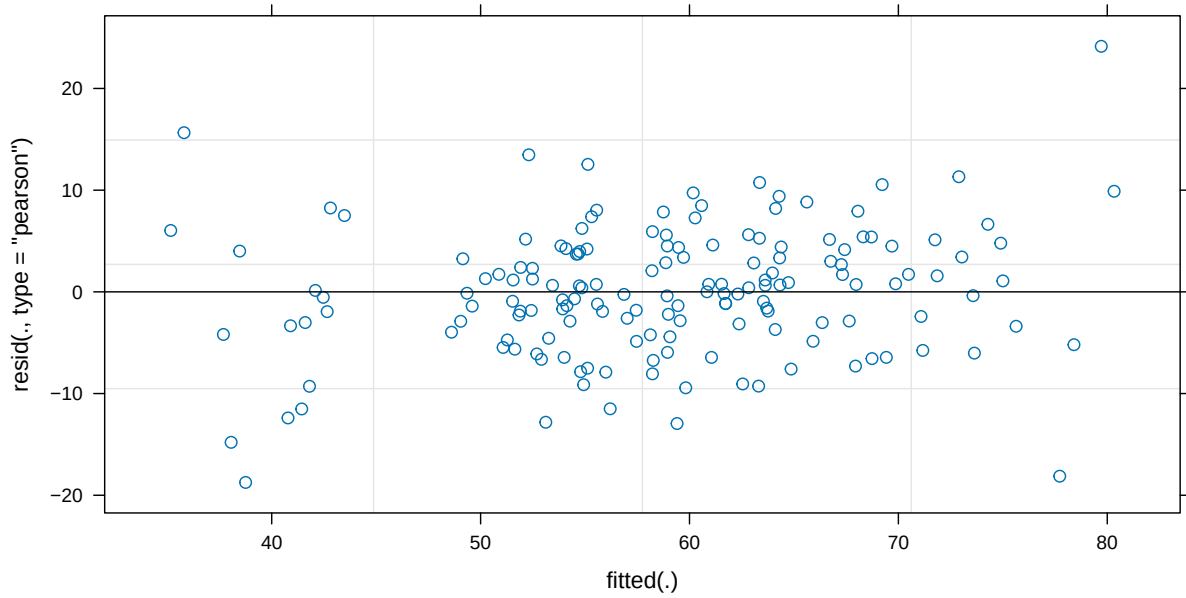
Evaluation plot for variable: Lateral MoS @ footstrike id # 3



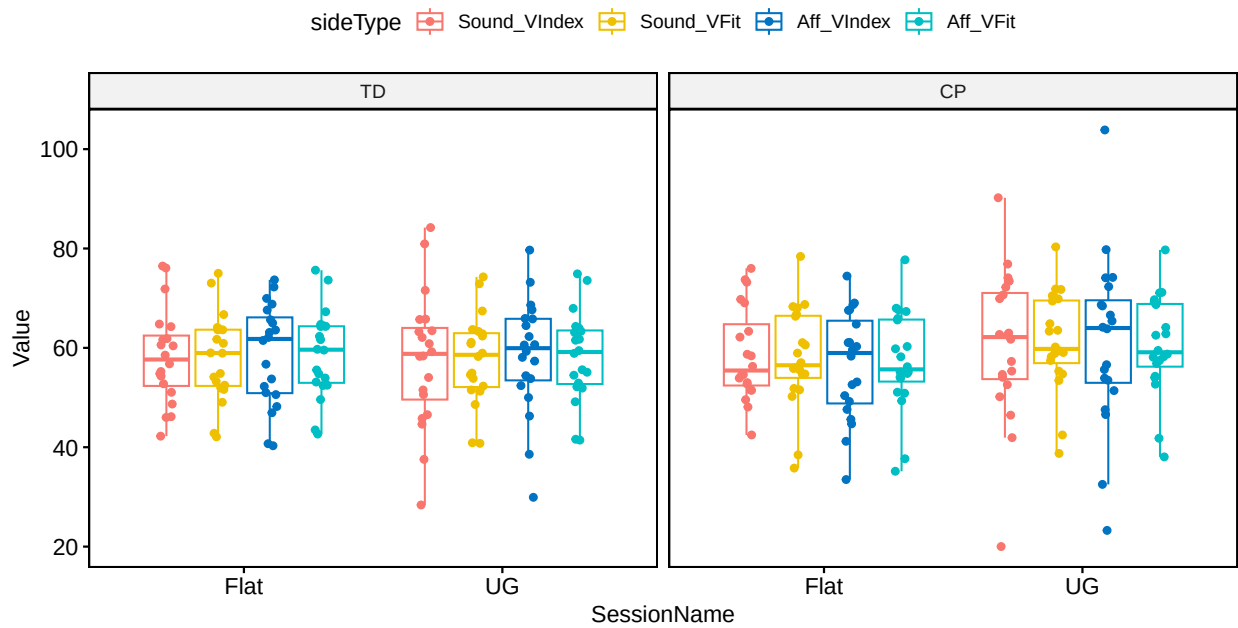
Box plot for variable: Lateral MoS @ footstrike id # 3



Evaluation plot for variable: Minimum lateral MoS id # 4



Box plot for variable: Minimum lateral MoS id # 4



3.8.4 Table of the model estimates

term	ant MoS	max ant MoS	lat MoS	min lat MoS
(Intercept)	251.7***	255.6***	83.1***	51.4***
SessionNameUG	6.8*	17.2***	3.4	0.3
SubjectGroupCP	10.0	-1.4	0.9	0.5
WSpeed	-543.3***	-459.0***	-16.8	14.6
SubjectGroupTD:SideAff	-3.4	-1.3	0.4	0.6
SubjectGroupCP:SideAff	-30.1***	-1.3	-1.4	-0.7
SessionNameUG:SubjectGroupCP	-3.7	-1.8	3.0	3.4